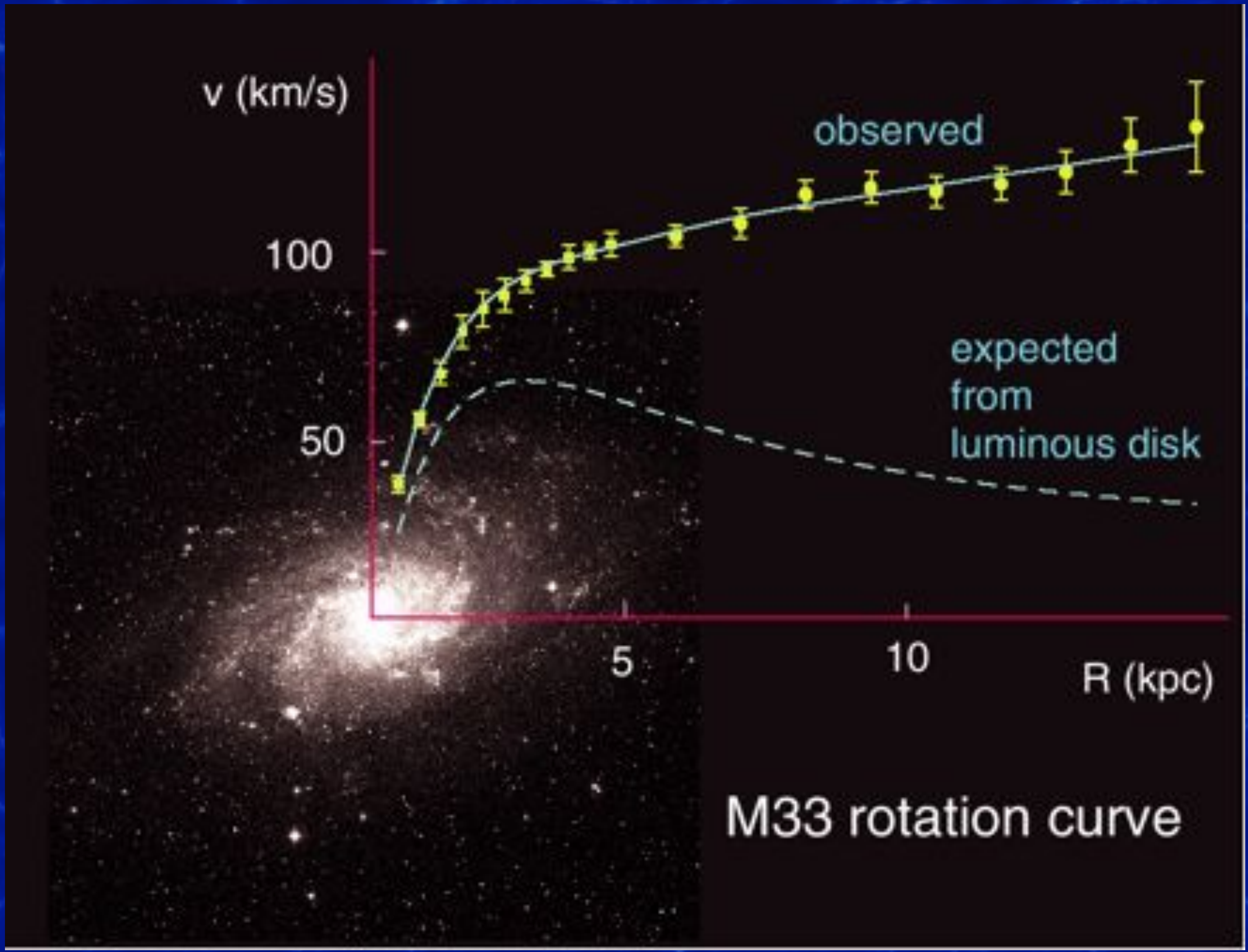
Direct Detection of Dark Matter

Jeter Hall

Fermi National Accelerator Laboratory

The Dark Matter Problem

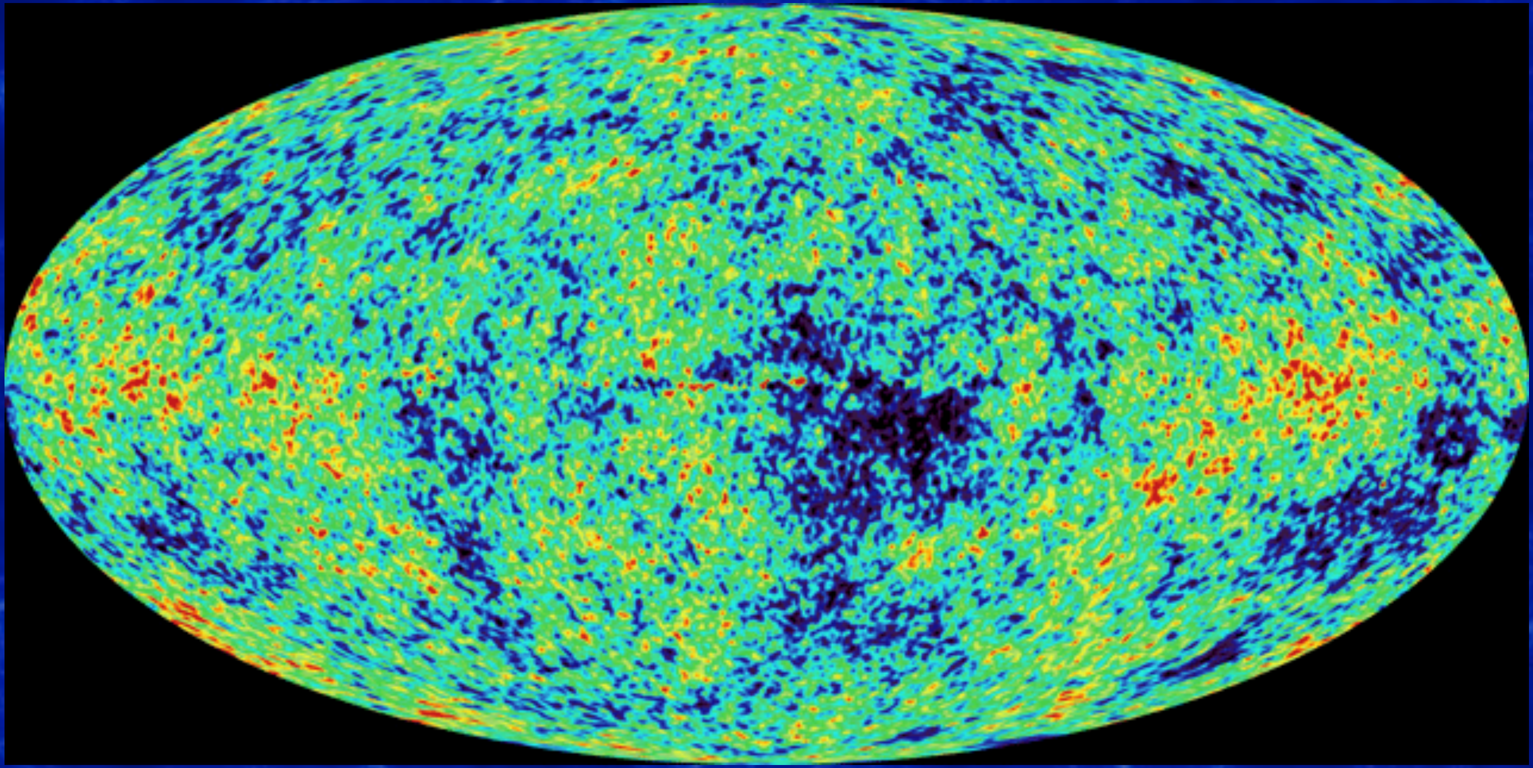


L. Bergstrom Rept.Prog.Phys. 63, 793 (2000)

The Dark Matter Problem

Clowe et al. ApJL 648, L109 (2006)

The Dark Matter Problem



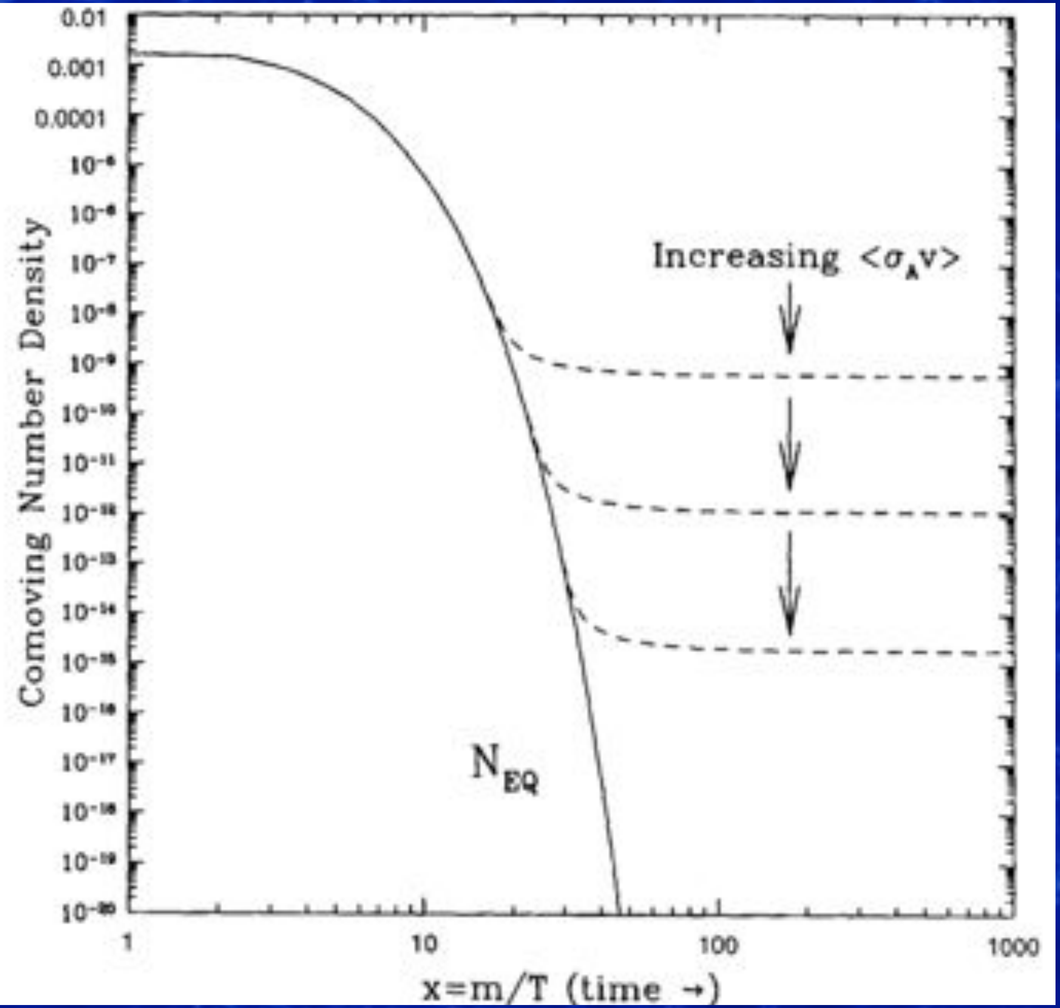
Wilkinson Microwave Anisotropy Probe

- Era of precision Cosmology (Hot big bang, accelerating expansion)

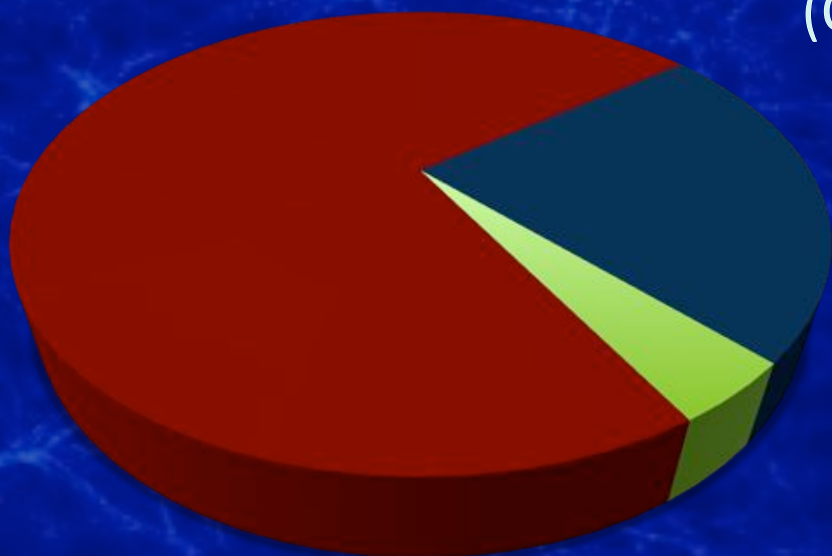
Thermal Relics

- Weak scale mass and annihilation cross-section yield a thermal relic density similar to the observed DM density

Equilibrium Annihilation Freeze-out



Composition of the Universe



Dark Matter
(Cold, Non-Baryonic)
~ 23%

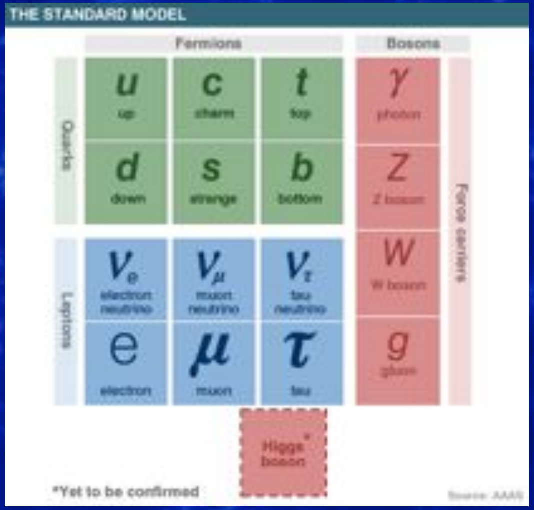
Dark Energy
~ 73%

Standard Model
~ 4%

Top Quarks $\sim e^{-10^{42}}$

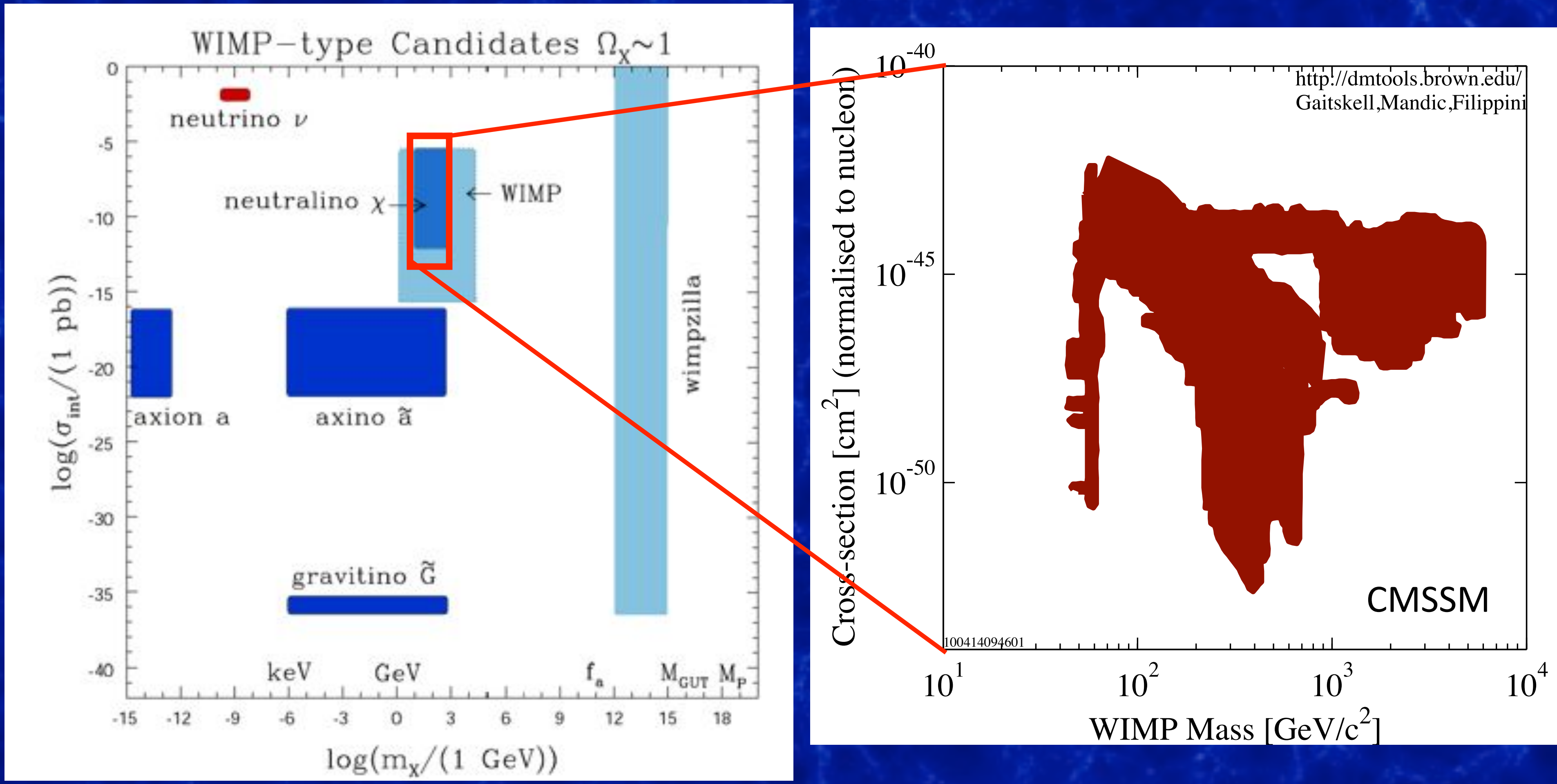
Neutrinos $\sim 10^{-4}$

- There are many mysteries in this era of precision cosmology



The Dark Matter Landscape

(how do you search for something when you don't know what it is?)

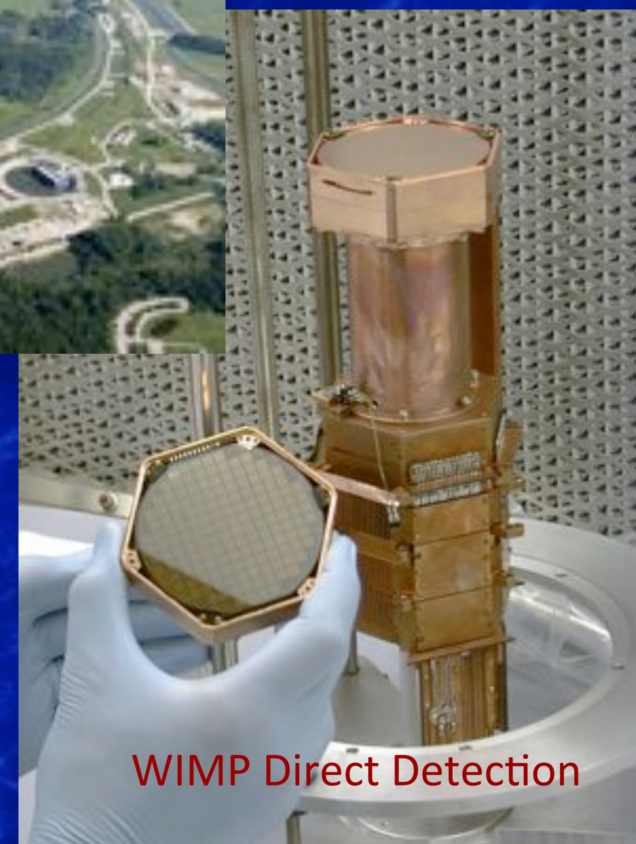


L. Roszkowski

Searching for WIMPs

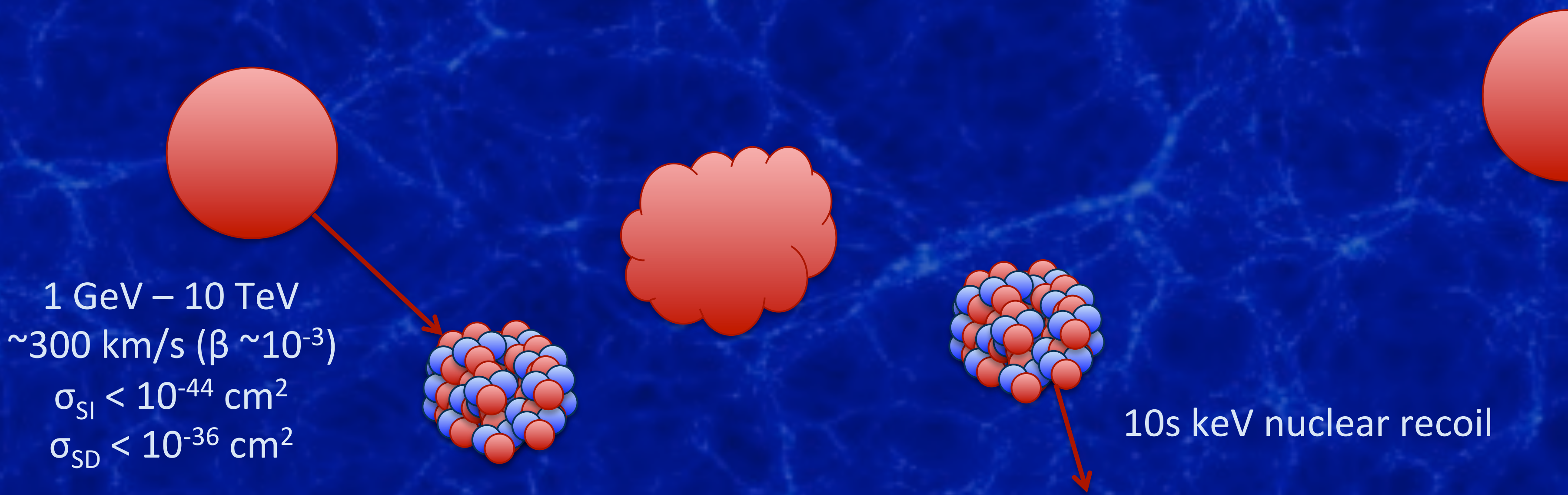

WIMP Production


WIMP Indirect Detection


WIMP Direct Detection

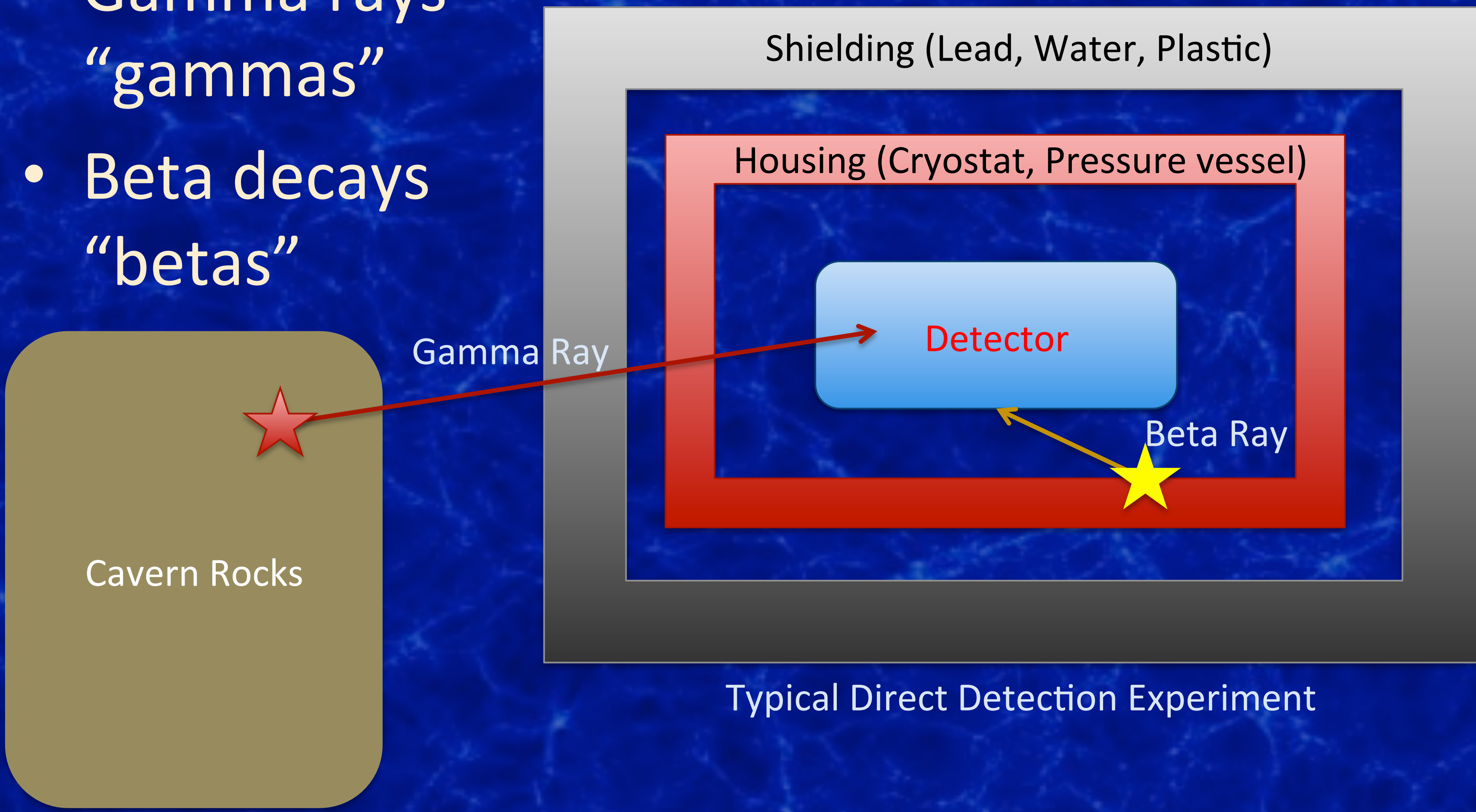
Direct Detection of Dark Matter

- Searching for WIMP-Nucleus elastic scattering
- In a sea of background radiation
  - Low background frontier



Electromagnetic Backgrounds

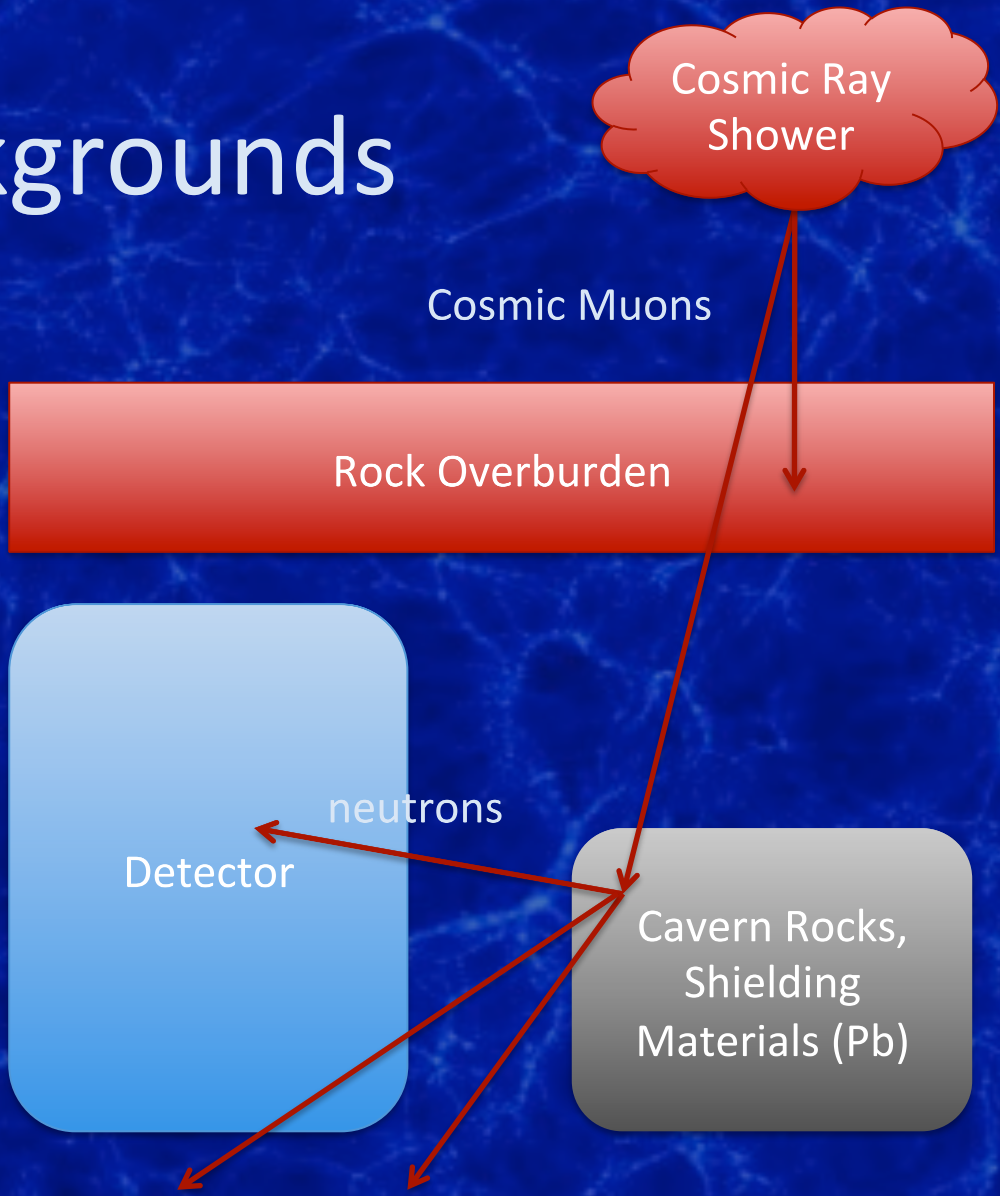
- Gamma rays
  “gammas”
- Beta decays
  “betas”



Typical Direct Detection Experiment

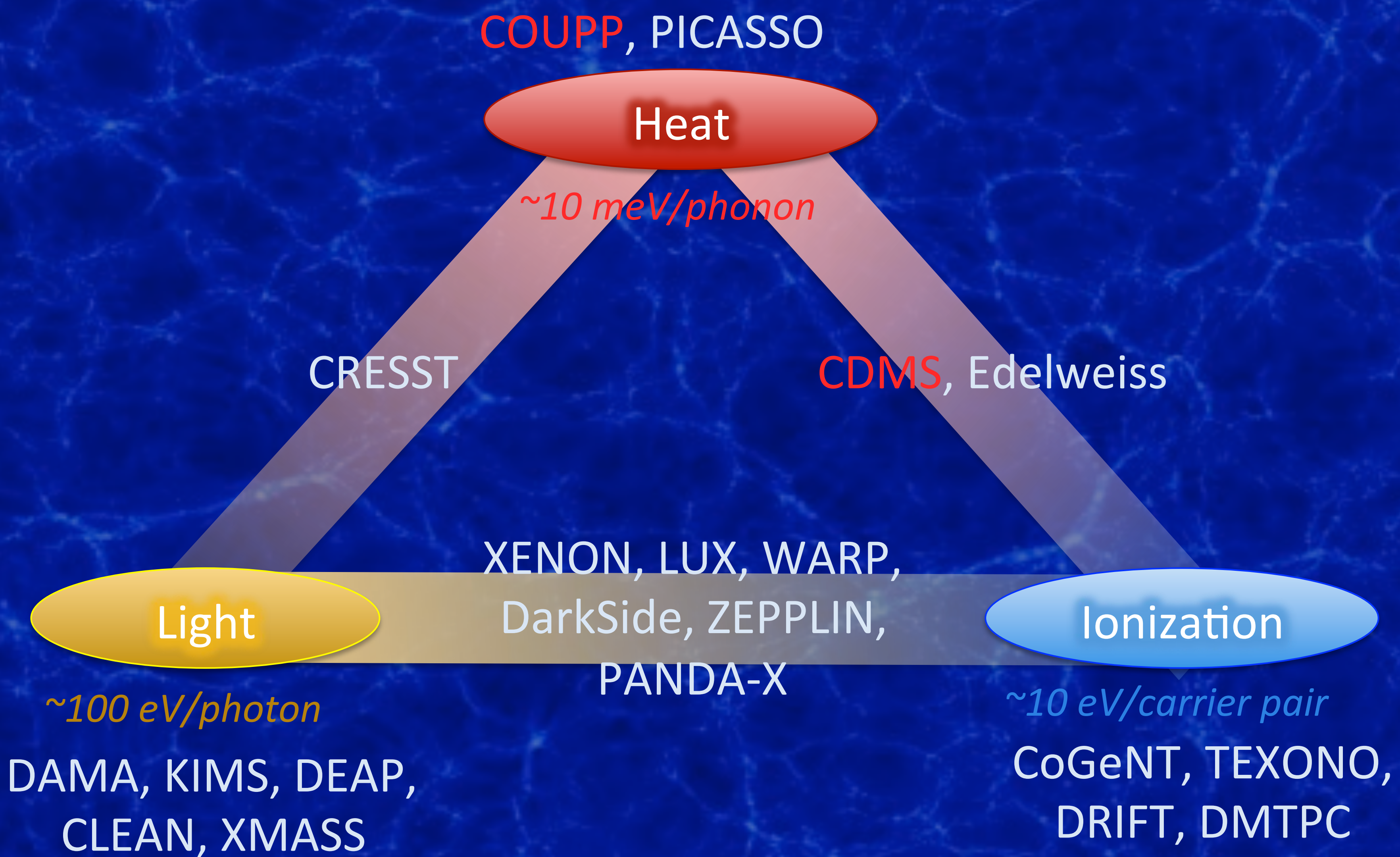
Neutron Backgrounds

- Creates nuclear recoils identical to WIMP scatters
- Neutron-nucleus elastic scattering "neutrons"
  - natural radioactivity*
  - high energy beams*
  - cosmic radiation*

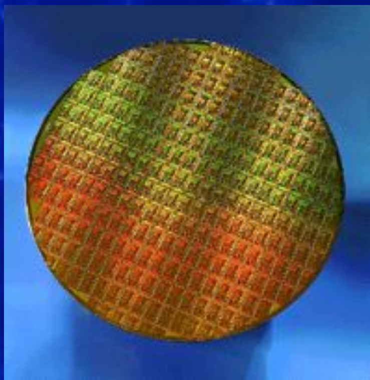


*Useful calibration source when tagged

Direct Detection Techniques

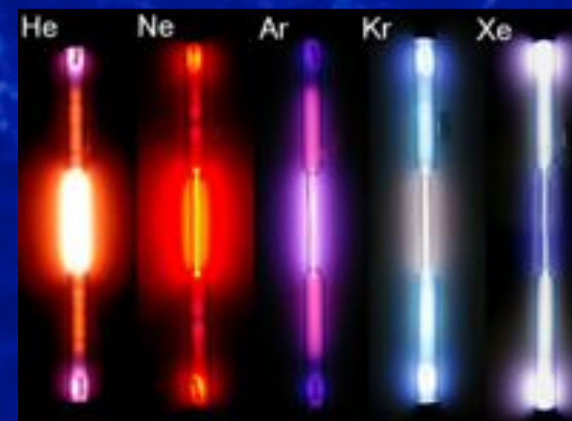


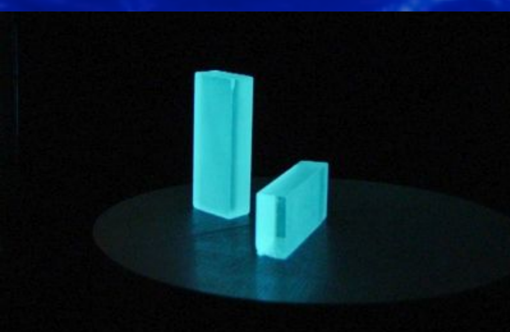
Direct Detection Targets



CDMS, Edelweiss,
CoGeNT, TEXONO

XENON, LUX, WARP,
DarkSide, ZEPPLIN,
PANDA-X, DEAP, CLEAN,
XMASS

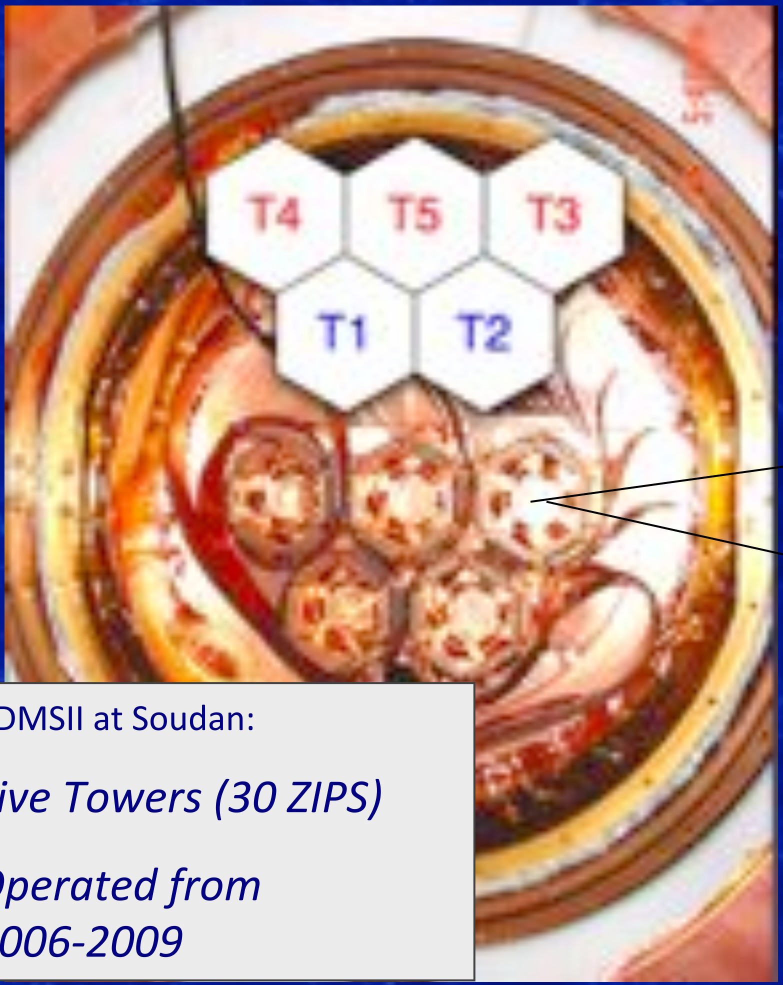




CRESST, DAMA,
KIMS

COUPP, PICASSO

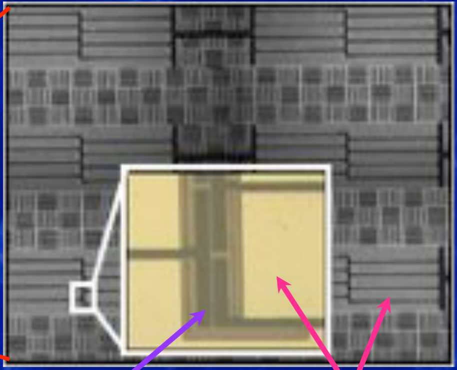
CDMS Overview



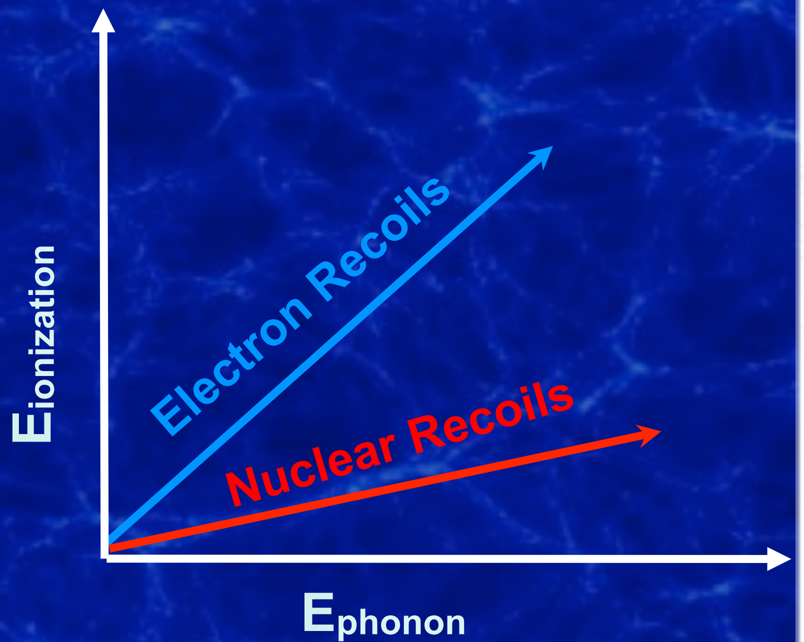
CDMSII at Soudan:

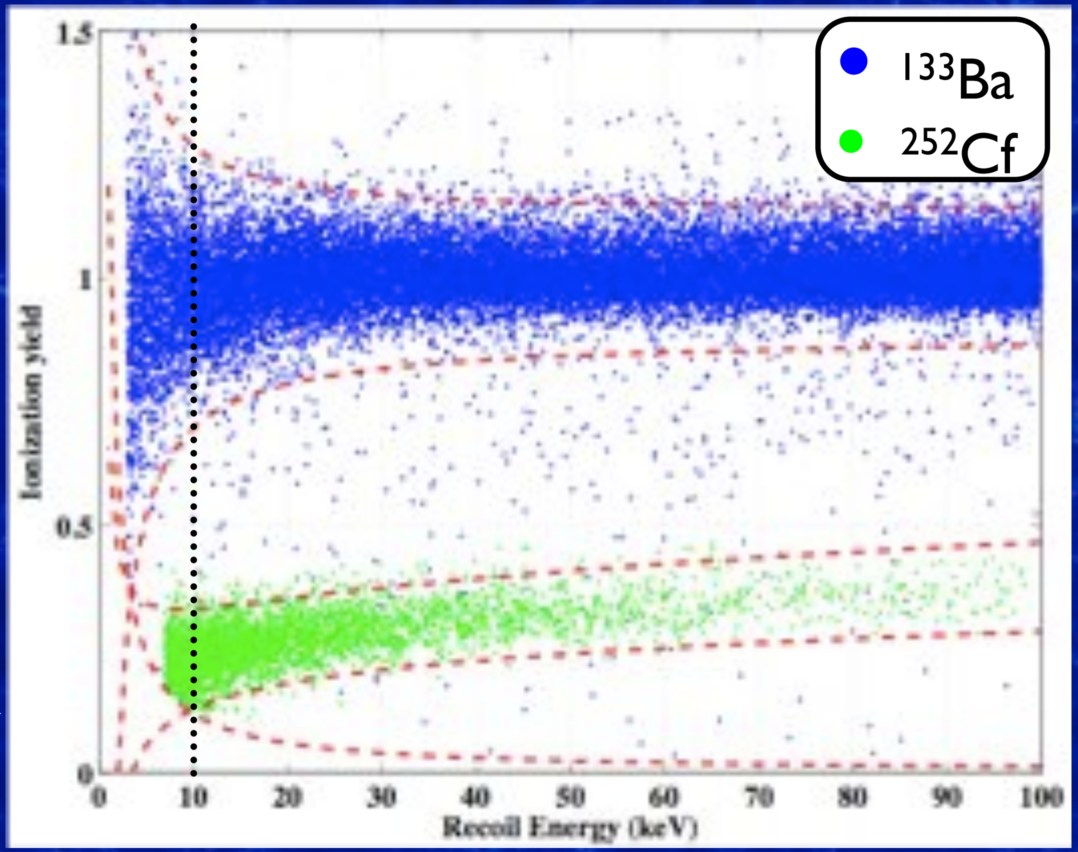
Five Towers (30 ZIPS)

Operated from 2006-2009



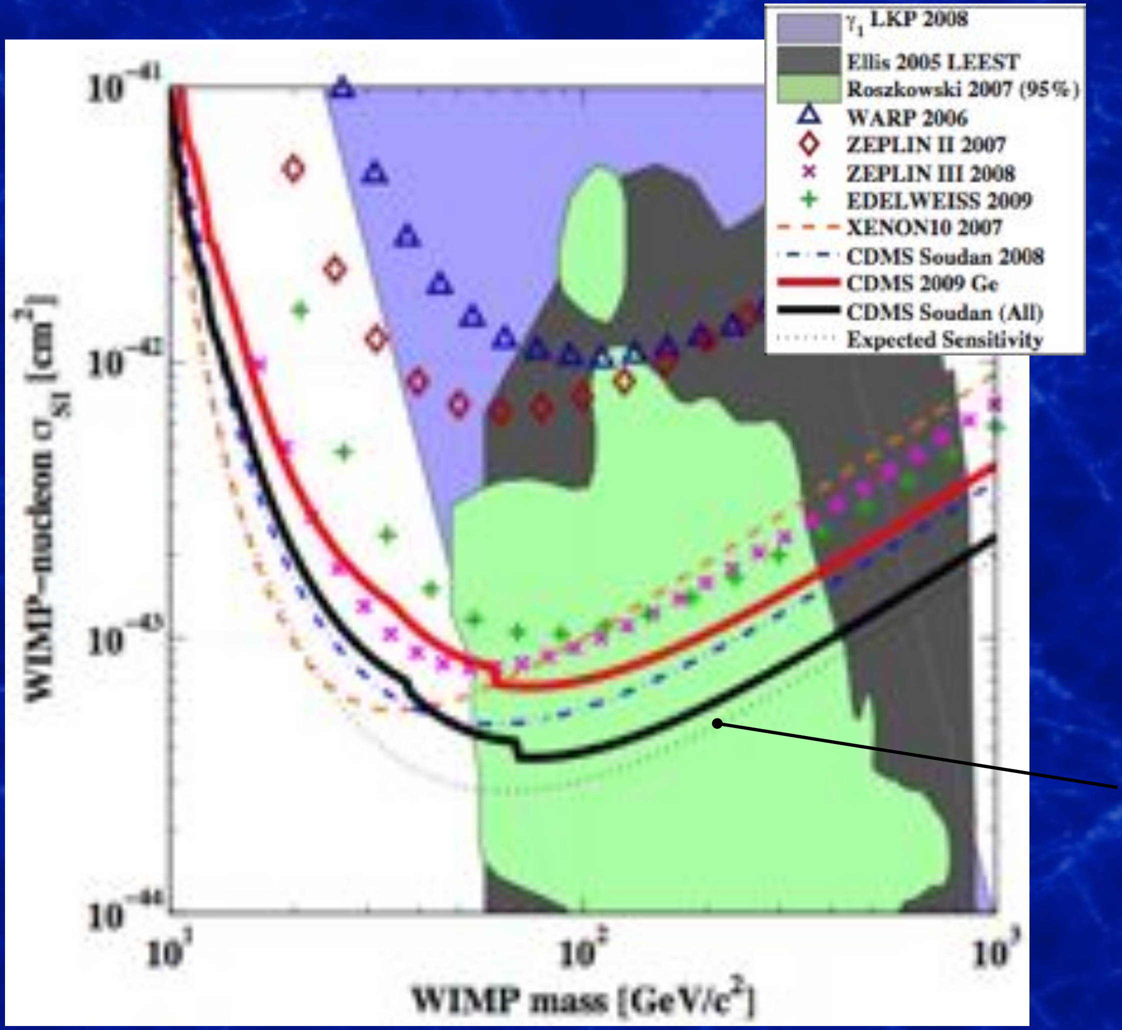
CDMS Discrimination





Better than 1:10^4 event by event gamma discrimination based on yield

CDMS WIMP Limits



Ahmed et al. Science 327, 1619 (2010)

CDMS Combined Soudan Data
@WIMP mass 70 GeV
$\sigma < 3.8 \times 10^{-44}$ cm^2 (90% C.L.)

After 2 years of exposure (350 kg days):

0.8 ± 0.1(stat.)± 0.2(sys.) beta events

$0.04^{+0.04}_{-0.03}$ cosmogenic neutrons

0.04 - 0.06 radiogenic neutrons

2 observed events consistent with total background expectation of 0.9 events

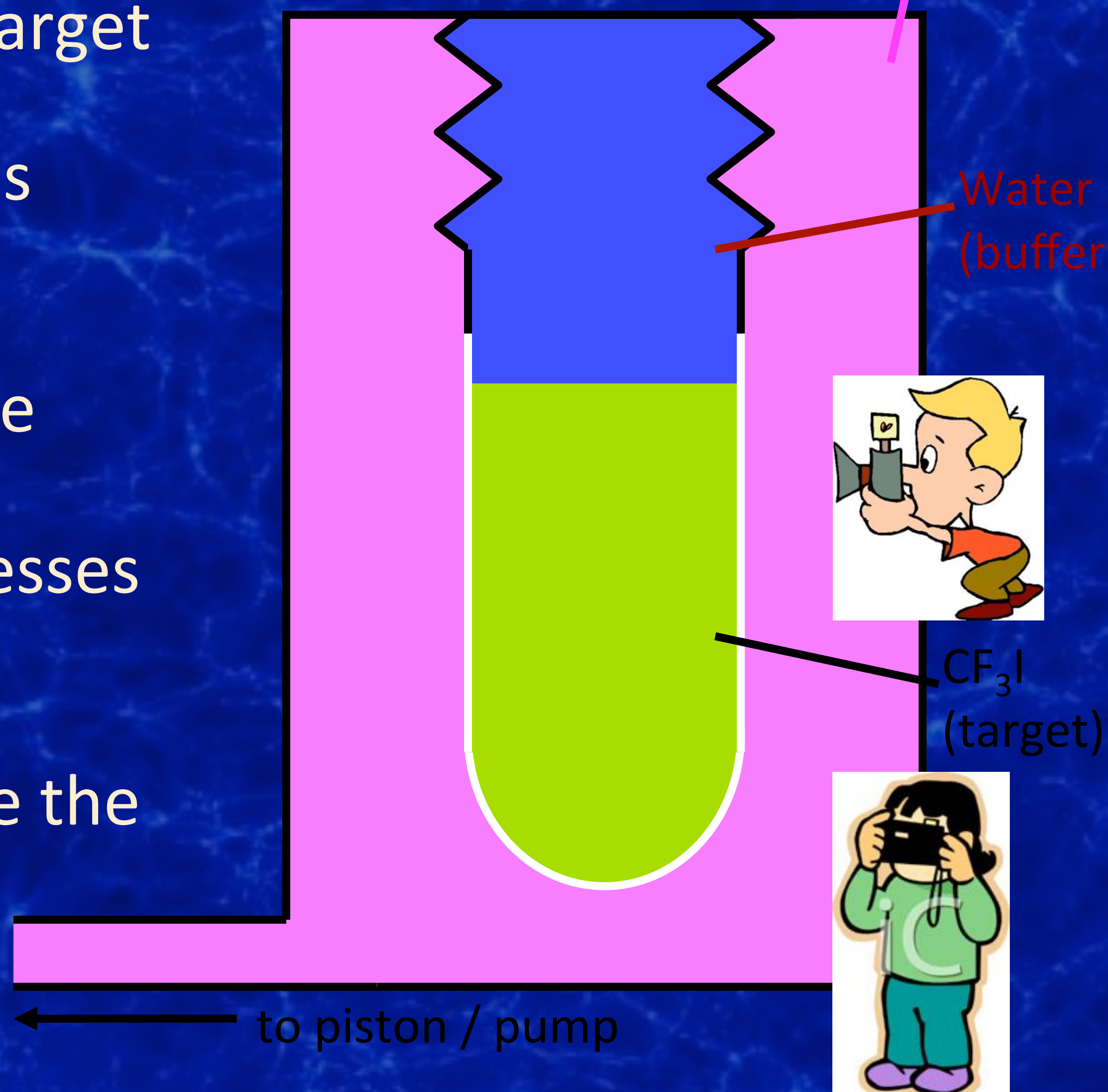
COUPP Overview

Spin-indep

- Superheated CF_3I target

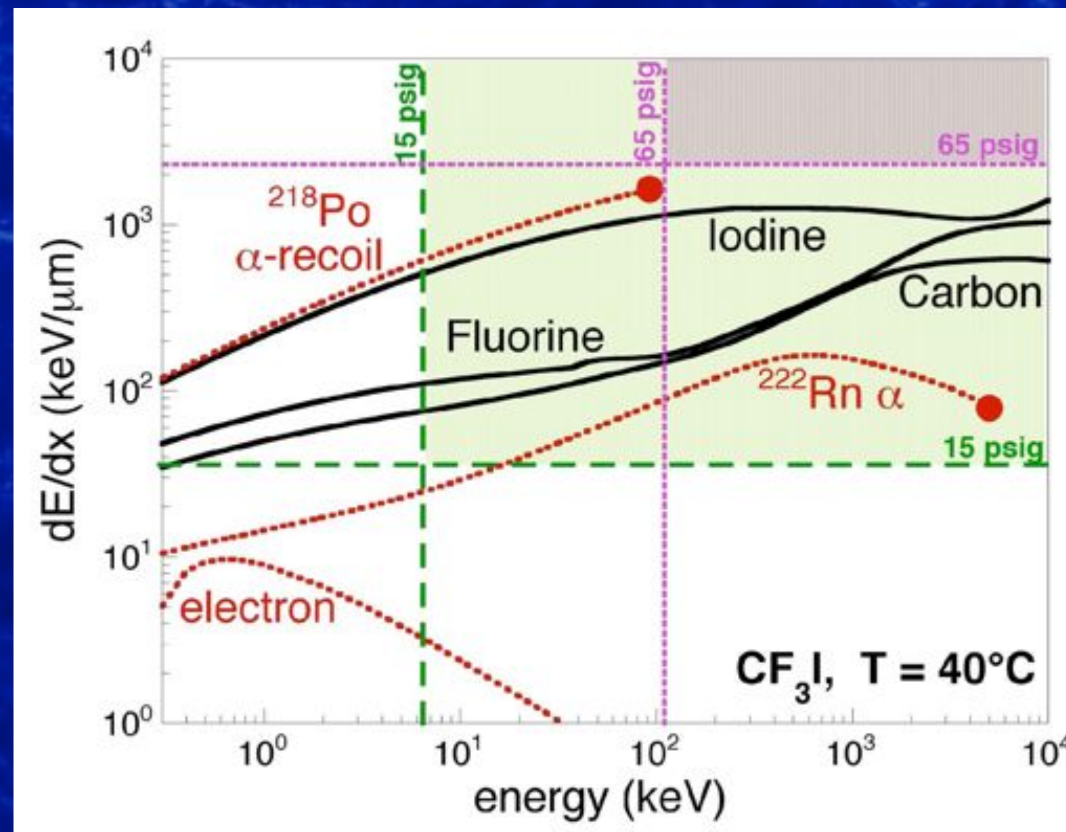
Spin-dep

- Particle interactions nucleate bubbles
- Cameras capture stereoscopic bubble images
- Chamber recompresses after each event
- Pressure and temperature define the operating point



COUPP Discrimination

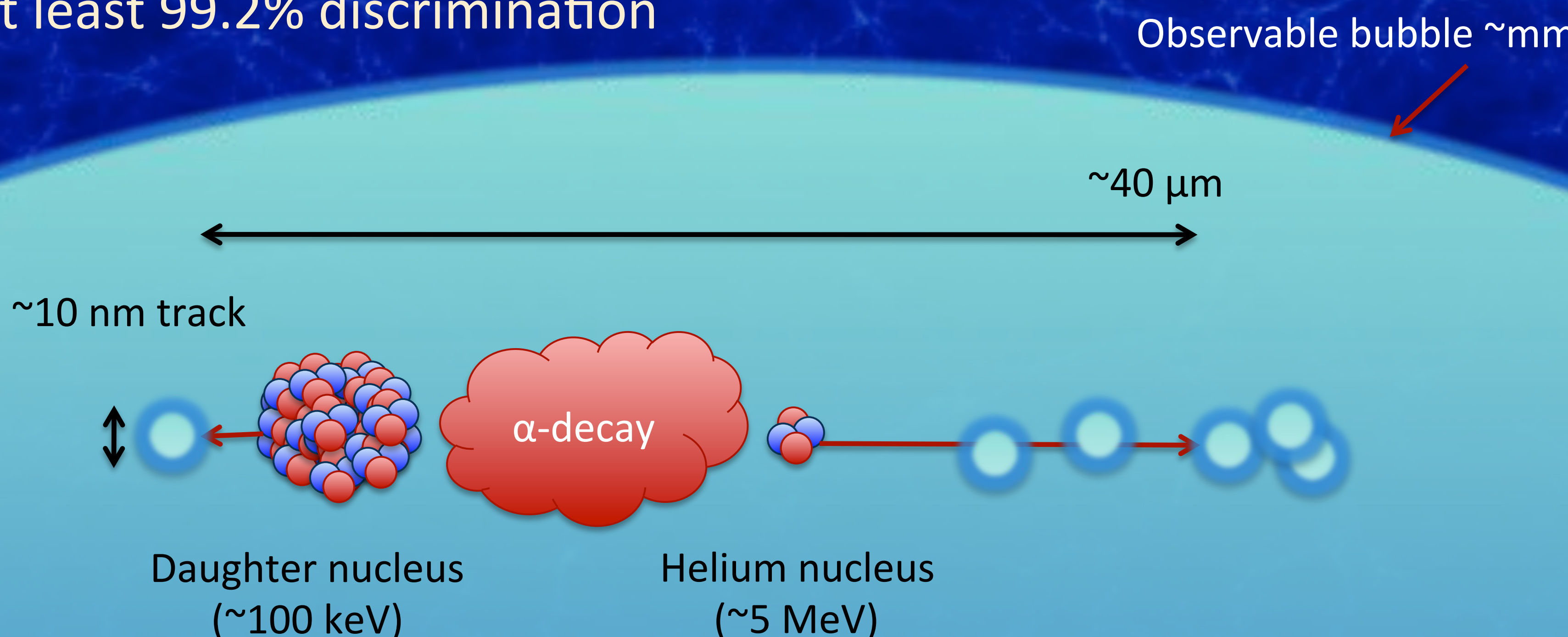
- Only proto-bubbles with $r > r_{crit}$ grow to be macroscopic
- Translates to two thresholds for bubble nucleation
  - Minimum Energy
  - Minimum dE/dx



α's do make bubbles

COUPP Acoustic Discrimination

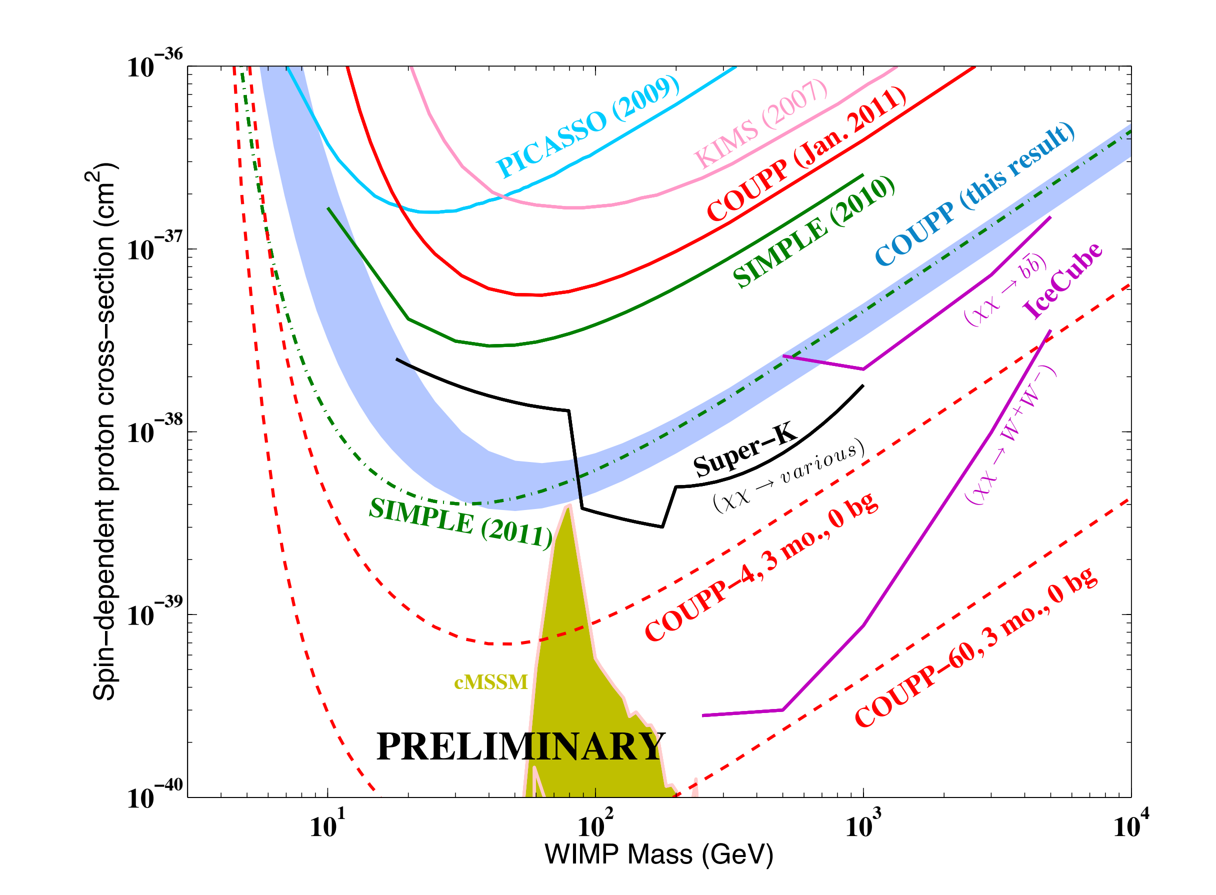
- High frequency acoustic information probes smaller scales
- Alpha decays produce tracks ~3 orders of magnitude longer, and they apparently produce more sound at high frequencies
- At least 99.2% discrimination



Behnke et al. PRL 106, 021303 (2011)

COUPP WIMP Limits

- 4 months running (300 kg day)
- Limits on spin dependent WIMP-proton couplings

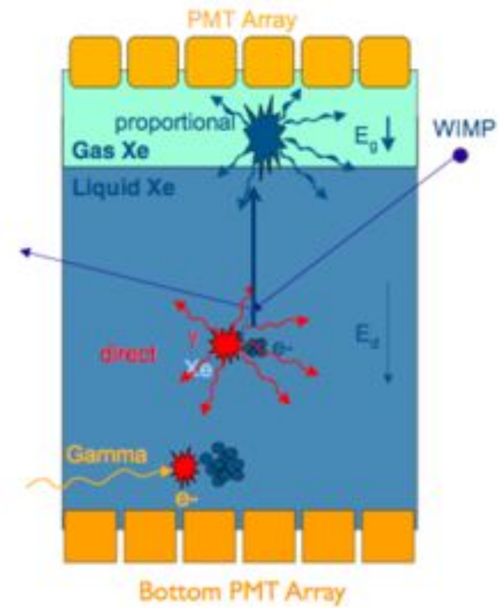


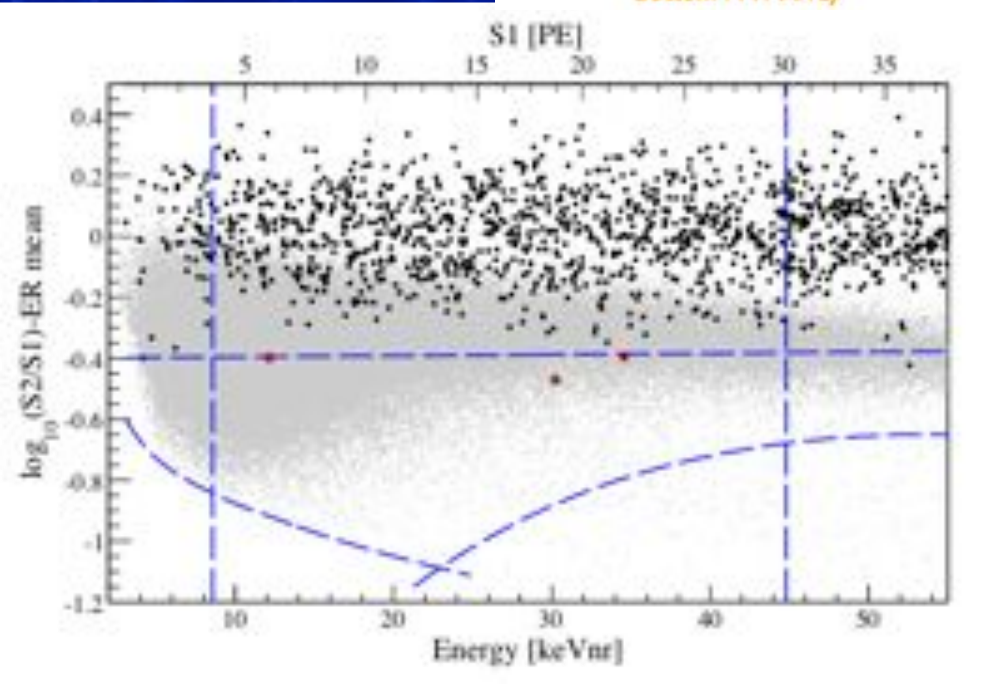
XENON Overview

- Liquid/Gas Xenon time projection chamber
- World's most sensitive spin-independent WIMP-nucleon search thus far

XENON Discrimination

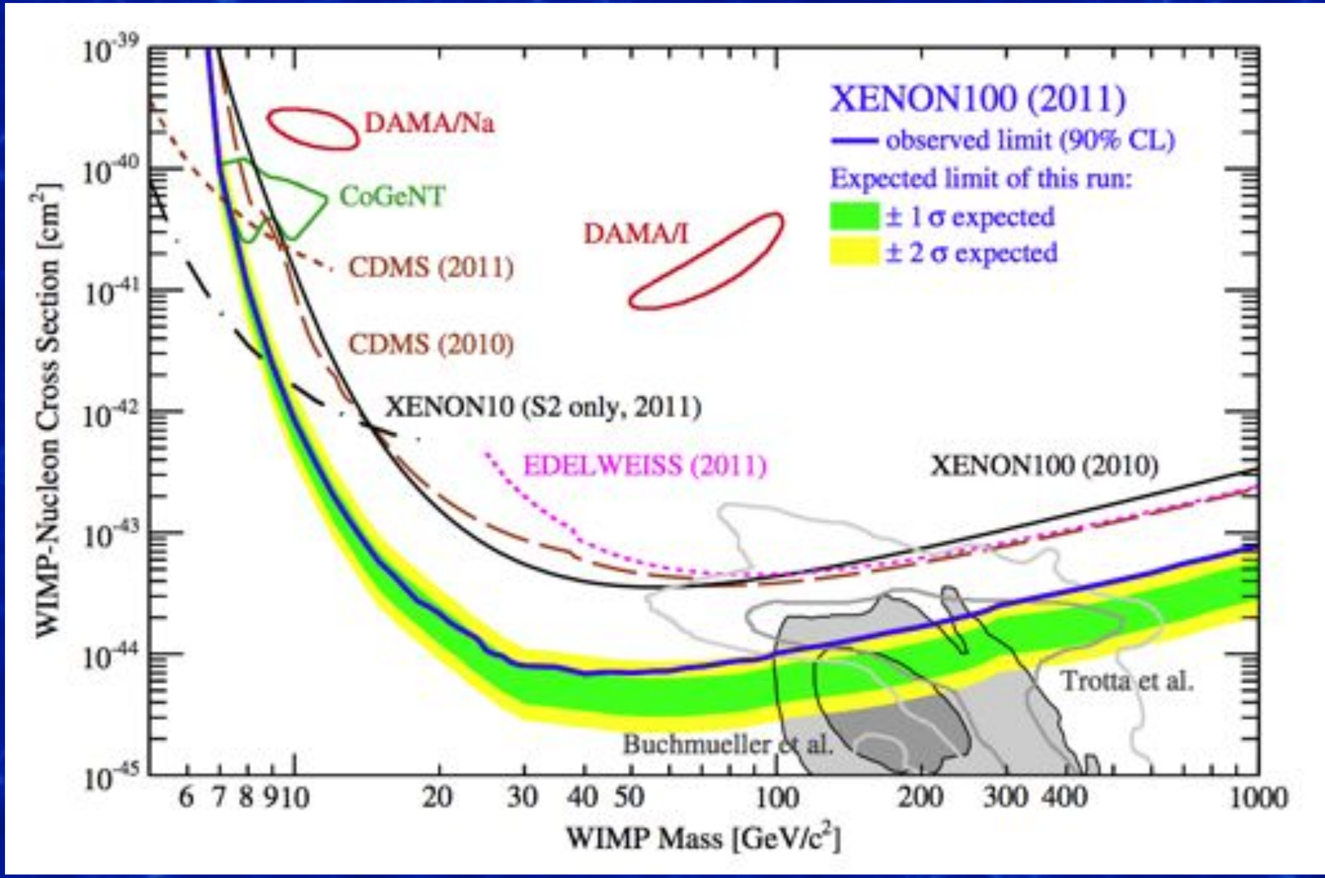
- Each interaction results in two flashes of light (S1 & S2)
- S1 is the initial scintillation light (proportional to total energy)
- S2 occurs when the ionized electrons drift into the gas region (proportional to ionization energy)
- Ratio separates electron and nuclear scattering (~99.5% discrimination)





XENON Limits

- 3 Months exposure (~2000 kg days)
- World's best spin-independent WIMP-nucleon dark matter limits



Aprile et al. PRL 107, 131302 (2011)

Summary

- Sensitivity to weakly interacting massive particles is rapidly increasing (~order of magnitude every 3 years) with a variety of experimental techniques
- Any theoretical and computational guidance is greatly appreciated and is required

Outline

- Dark Matter Problem
- Cryogenic Dark Matter Search
- Light Dark Matter

The Cryogenic Dark Matter Search

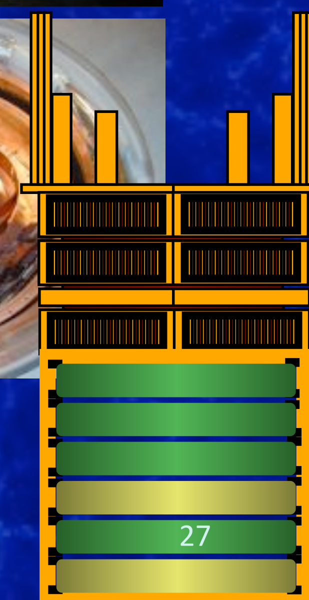
California Institute of Technology
Case Western Reserve University
Fermi National Accelerator Laboratory
Massachusetts Institute of Technology
NIST *
Queen's University*
Santa Clara University
Southern Methodist University*
SLAC/KIPAC *

Stanford University
Syracuse University
Texas A&M
University of California, Berkeley
University of California, Santa Barbara
University of Colorado Denver
University of Florida
University of Minnesota
University of Zurich

20 institutions, 30 Faculty and Scientists, 70 Students and Postdocs

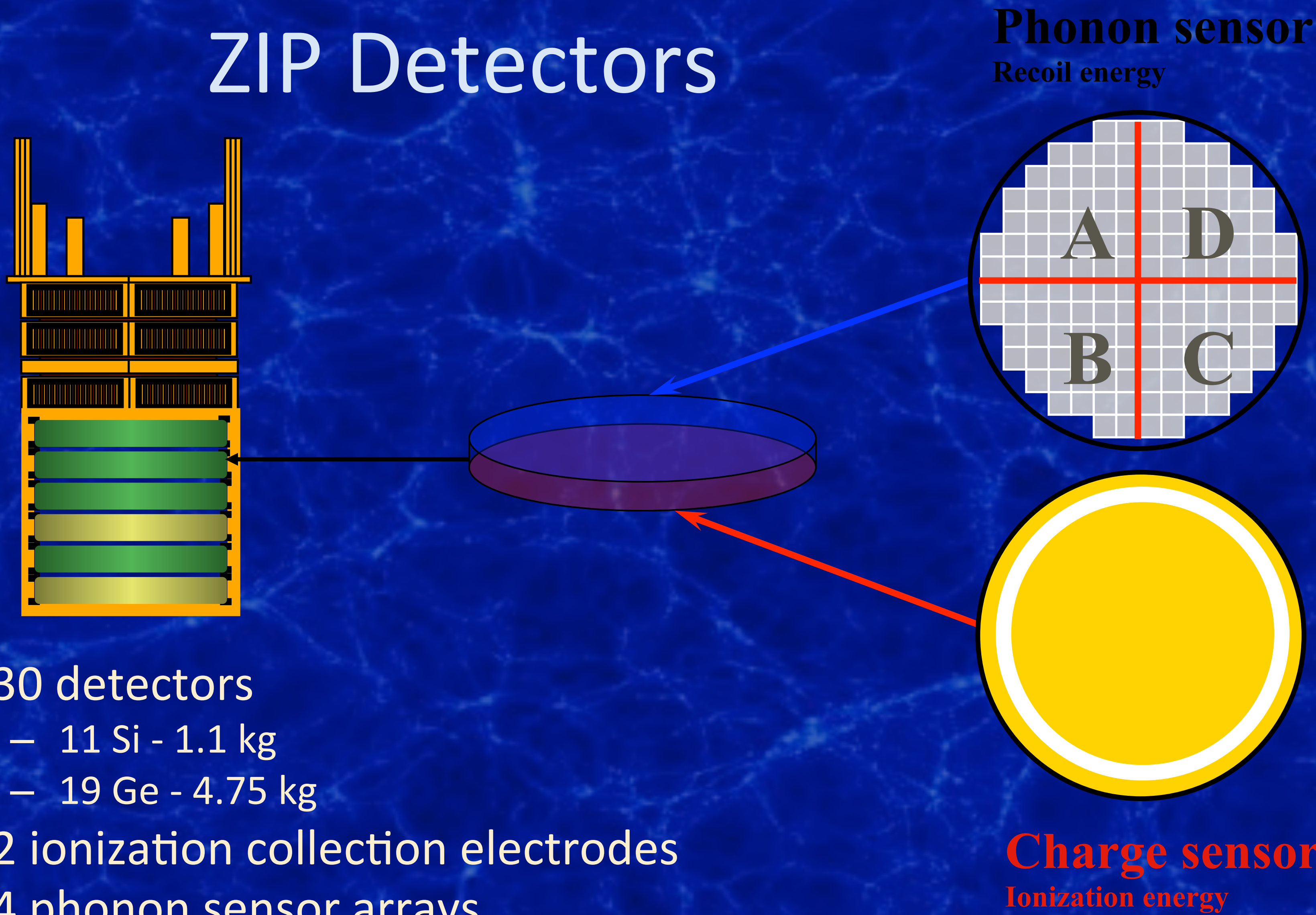
** new collaborators or new institutions in SuperCDMS*

Shielding/Radiopurity



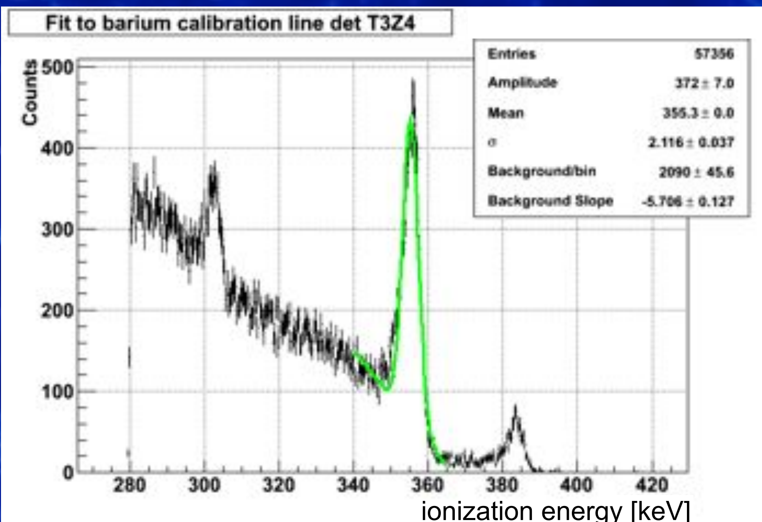
- 2000 m.w.e. (0.5 mile) rock overburden
- Plastic scintillator active veto
- 20 cm lead
- 50 cm polyethylene
- Copper cryostat
- 1 mm silicon endcaps
- Gaps between detectors minimized
- Rigorous cleanliness

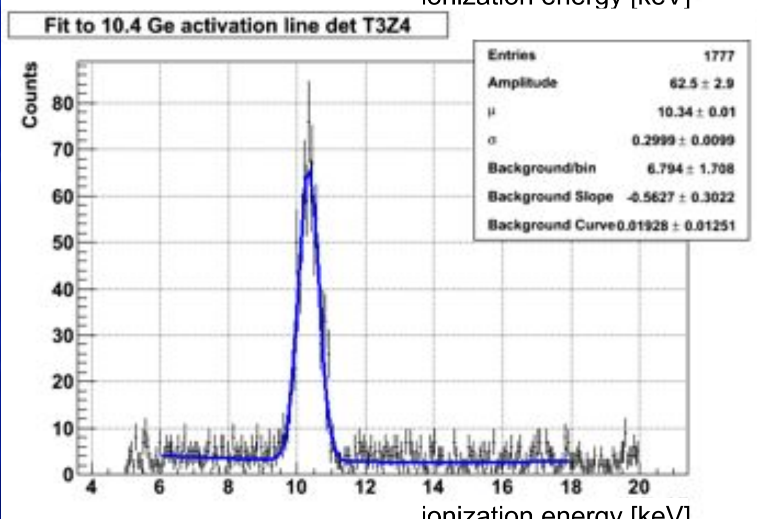
ZIP Detectors

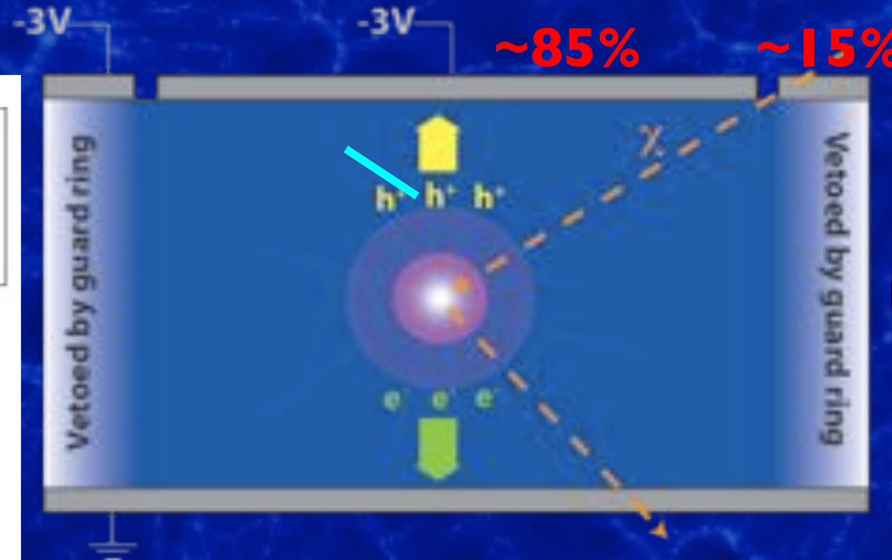


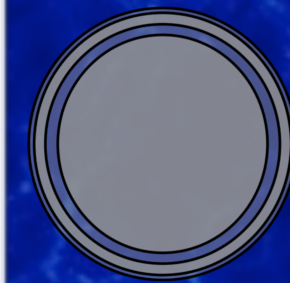
- 30 detectors
  - 11 Si - 1.1 kg
  - 19 Ge - 4.75 kg
- 2 ionization collection electrodes
- 4 phonon sensor arrays

Ionization Measurement









Complete collection at **3V/cm** (after trap neutralization)

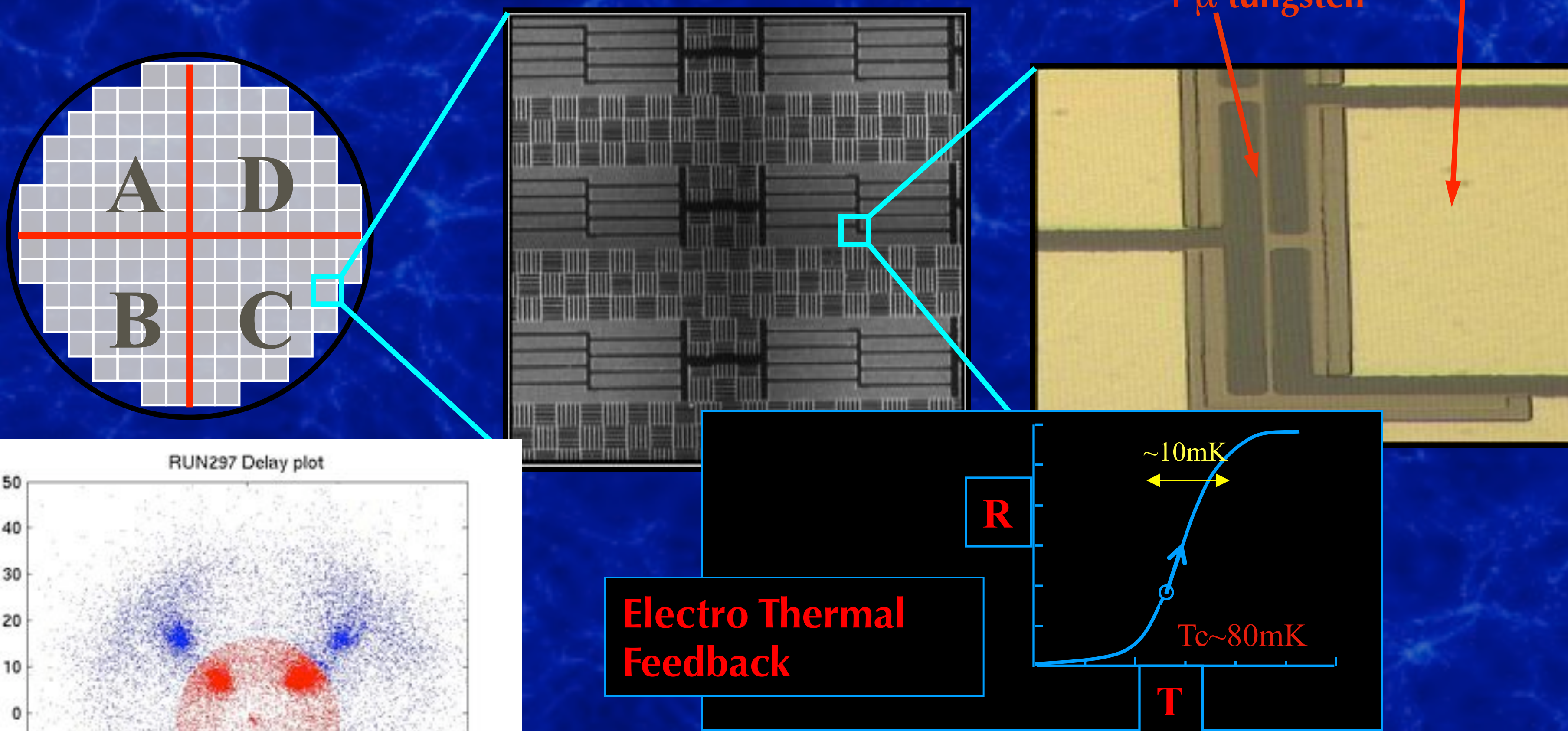
Low-noise JFET amp at 140 K: Zero-energy resolution **~100 e** (~0.5% @ 511 keV)

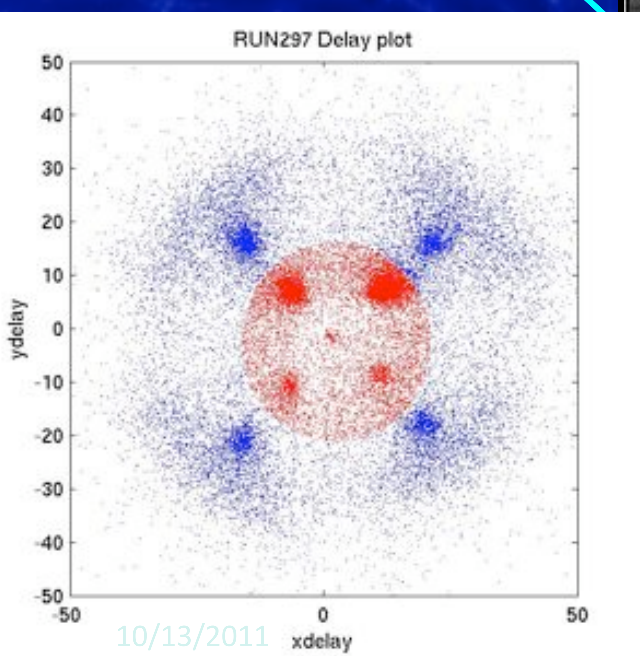
Charge = $E_{ionization}/\varepsilon$

ε_{Si} = 4 eV

ε_{Ge} = 3 eV

Phonon Measurement

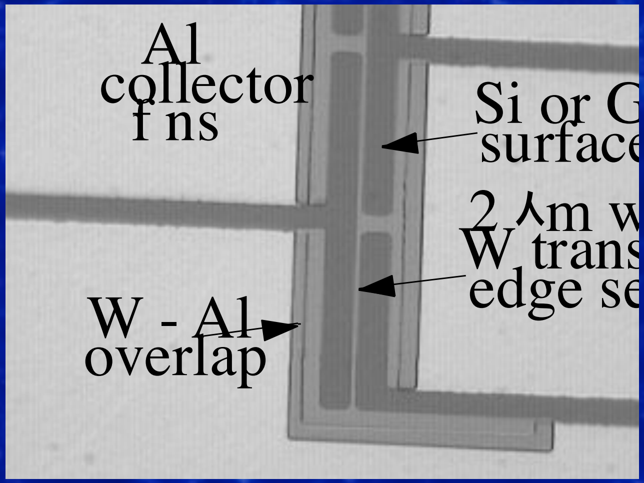


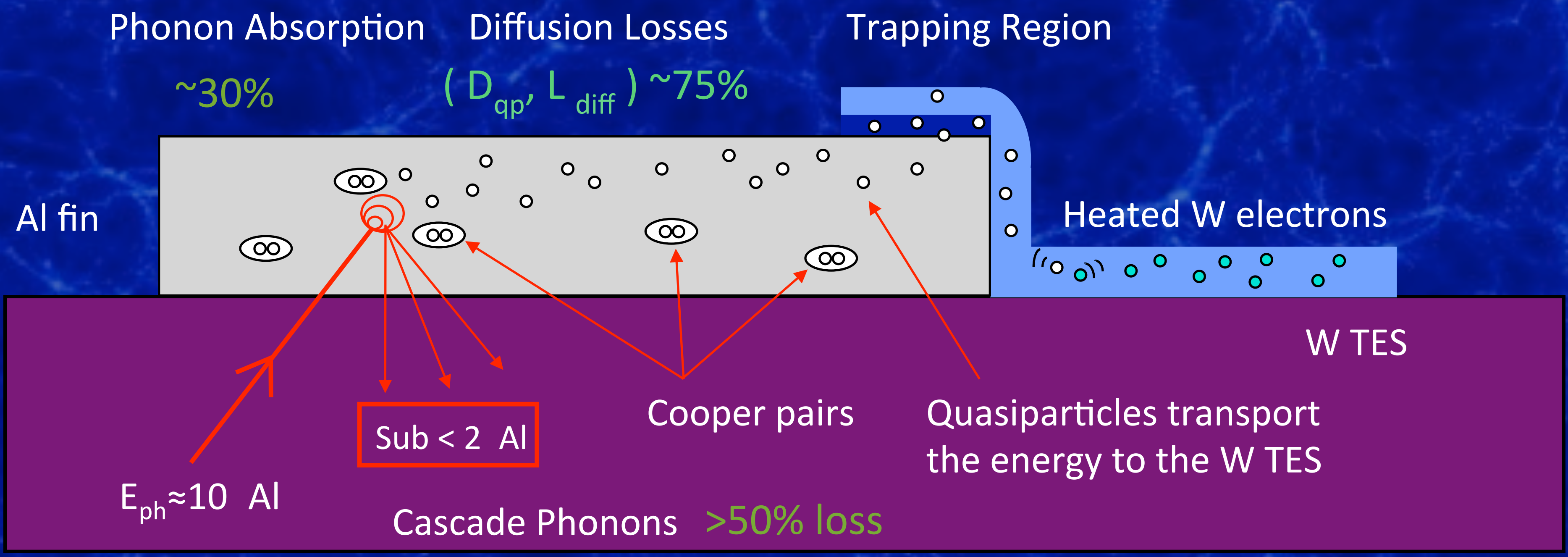


$$E_{phonon} = E_{recoil} + V \times E_{ionization}/\varepsilon$$

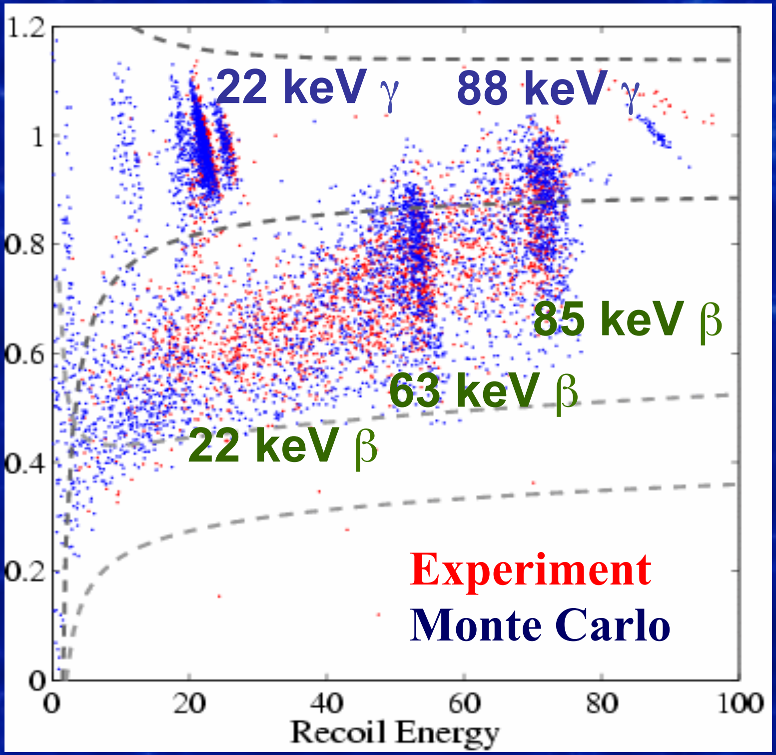
Athermal Phonon Sensors

- High-energy phonons (~400 GHz) from particle recoil break Cooper pairs in superconducting Al (Tc = 1 K). The Al film acts as a 'phonon filter' against other heating mechanisms.
- Resultant quasiparticles diffuse towards the tungsten trap where electron scattering heats up the W tungsten transition edge sensors (Tc ~ 70 mK)

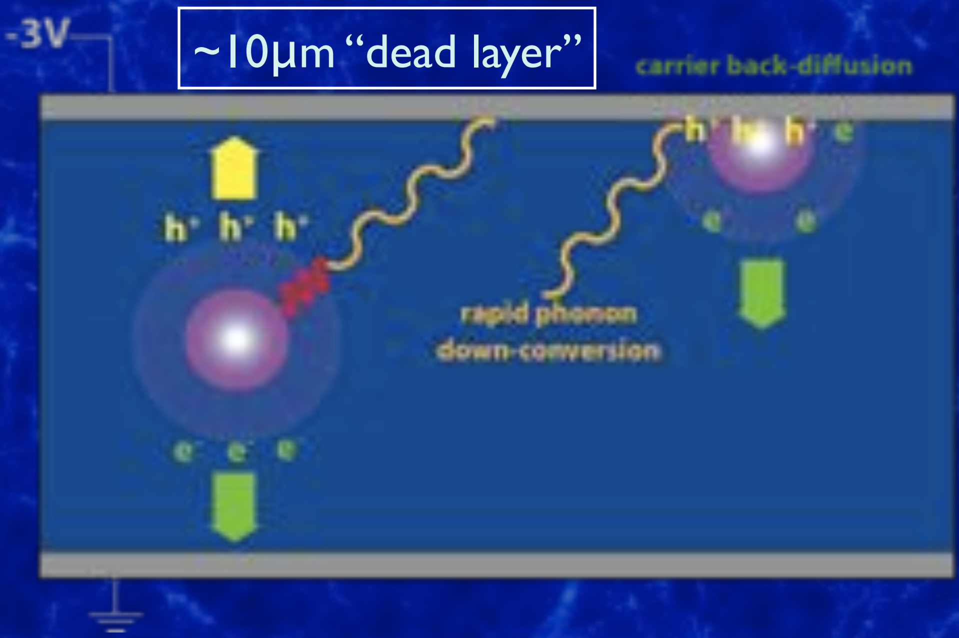




Surface Events

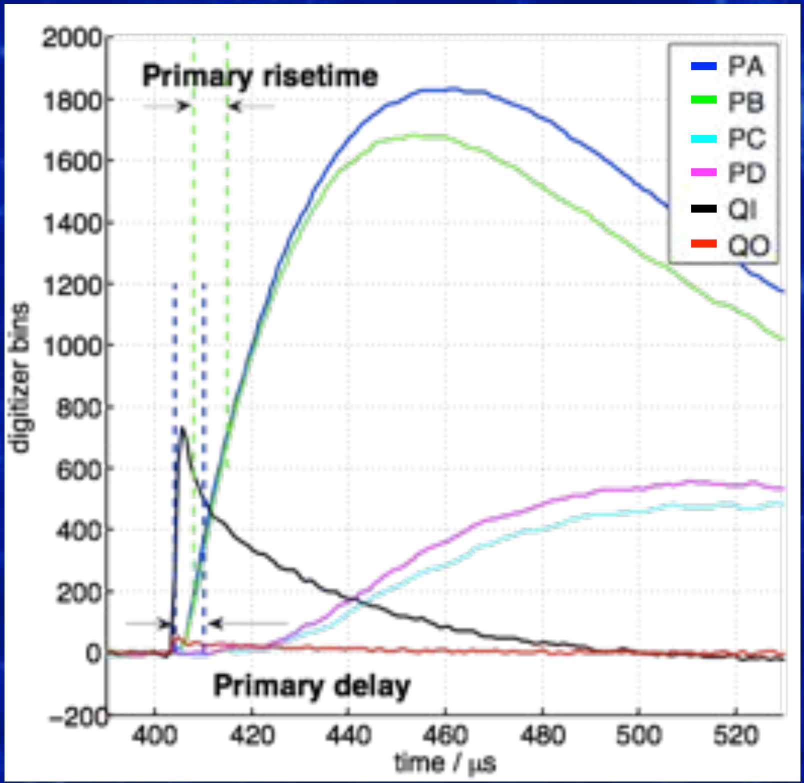


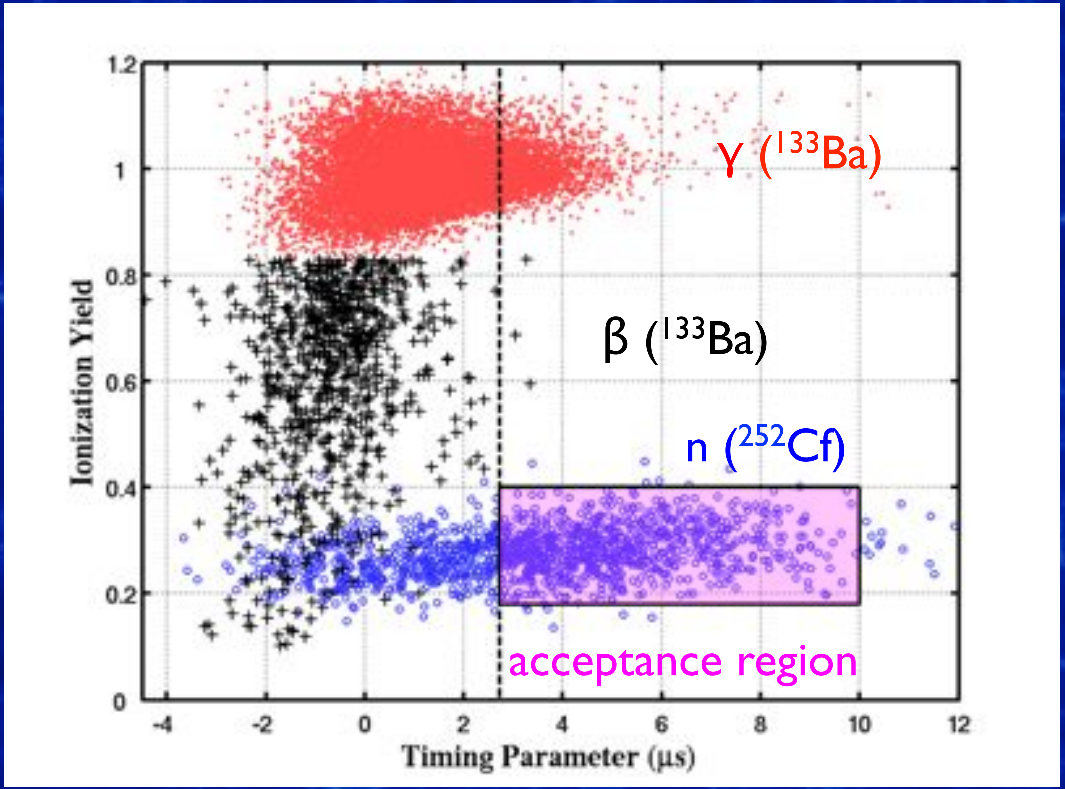
Cd-109 Calibration Data



- Surface backgrounds due beta and low energy gamma radiation
- Back diffusion of electrons/holes reduces measured ionization energy
- Single scatter surface event rate ~0.4 / kg / day

Residual Surface Backgrounds





- Surface events are faster due to rapid phonon down-conversion
- Cut on timing (delay + risetime), optimized for best sensitivity
- Surface event acceptance ~1:200
- Dominant background, but rejection can be improved with mild loss of efficiency

Blind Analysis (Backgrounds)

$$\text{Expected surface leakage} = \frac{N^{\text{sideband}}_{\text{passing cut}}}{N^{\text{sideband}}_{\text{failing cut}}} * N^{\text{data}}_{\text{failing cut}}$$

3 independent sidebands for estimating the passing/failing ratio

SIDEBAND 1

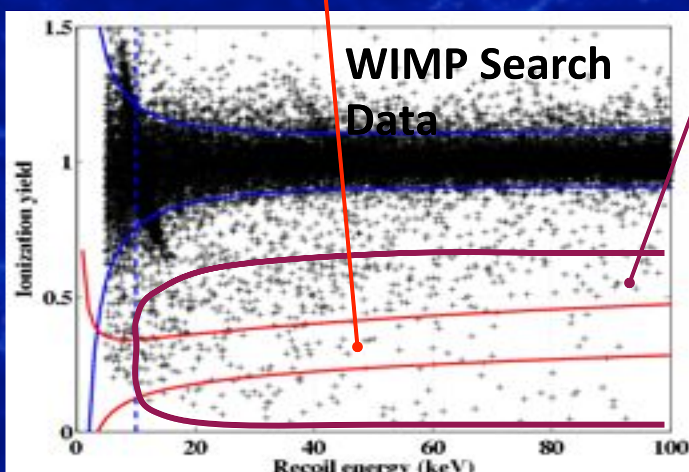
Use multiple-scatters in NR band

SIDEBAND 2

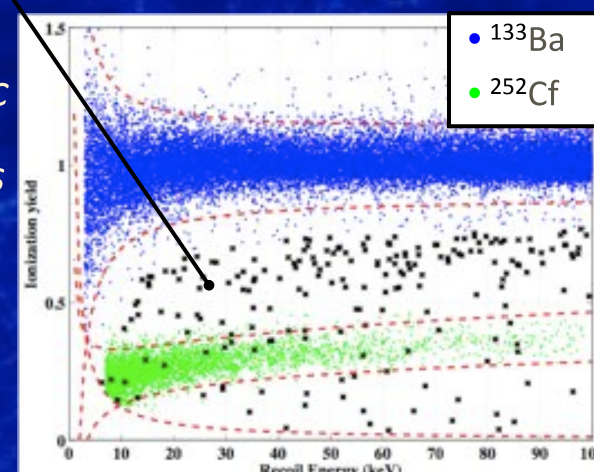
Use singles and multiples just outside NR band

SIDEBAND 3

Use singles and multiples from Ba calibration in wide region

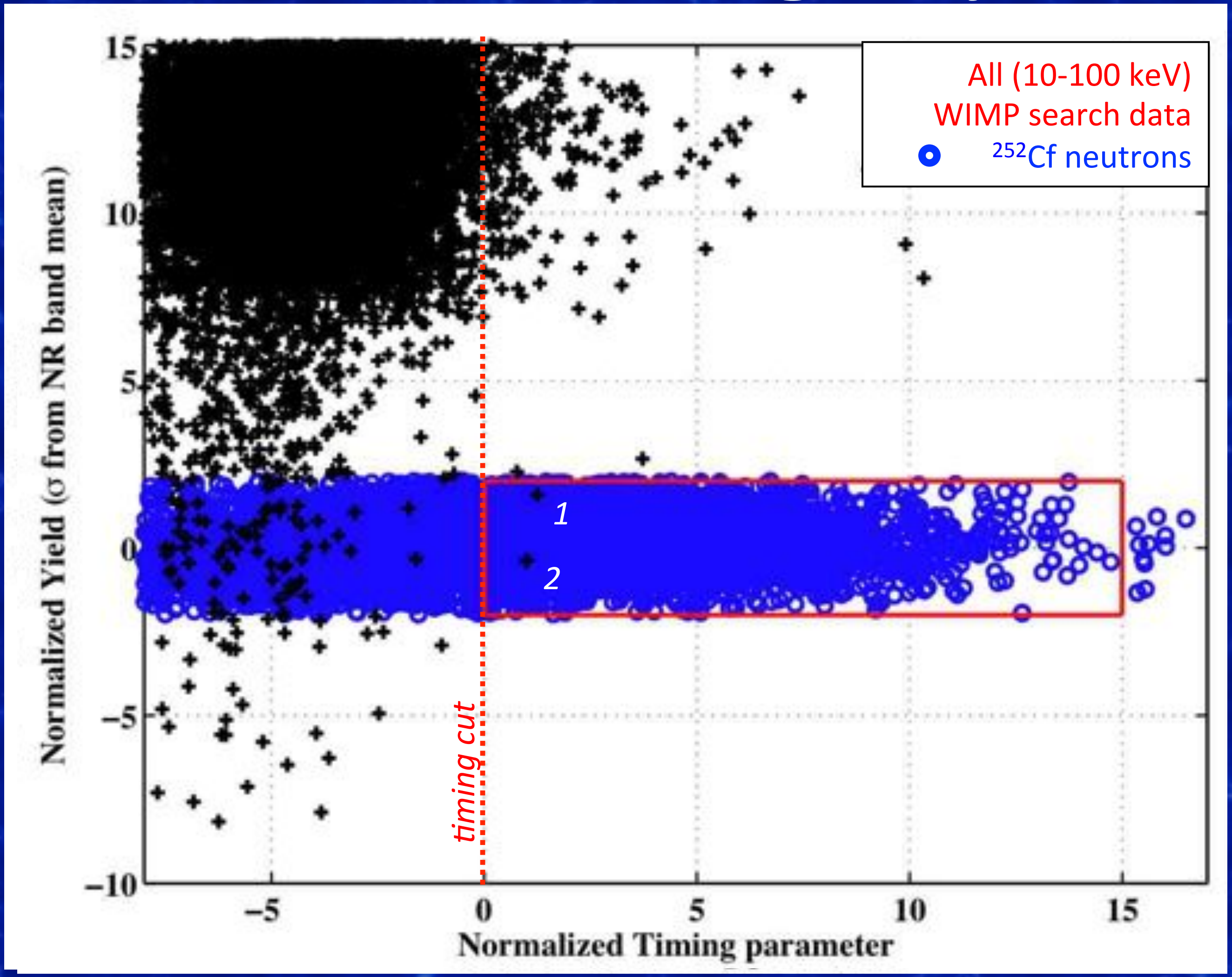


Correct for systematic effects due to different distributions in energy and yield



All 3 consistent, blind estimate = 0.6 ± 0.1 (stat) events

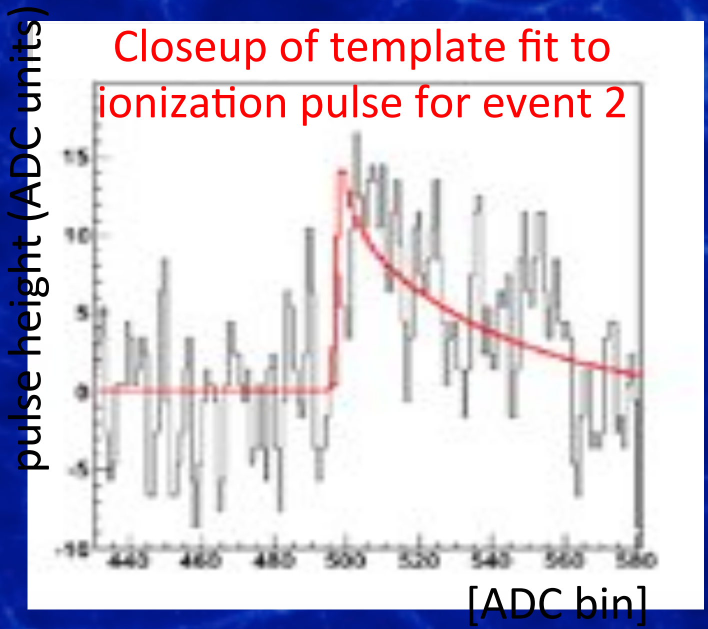
Results (191 kg day)



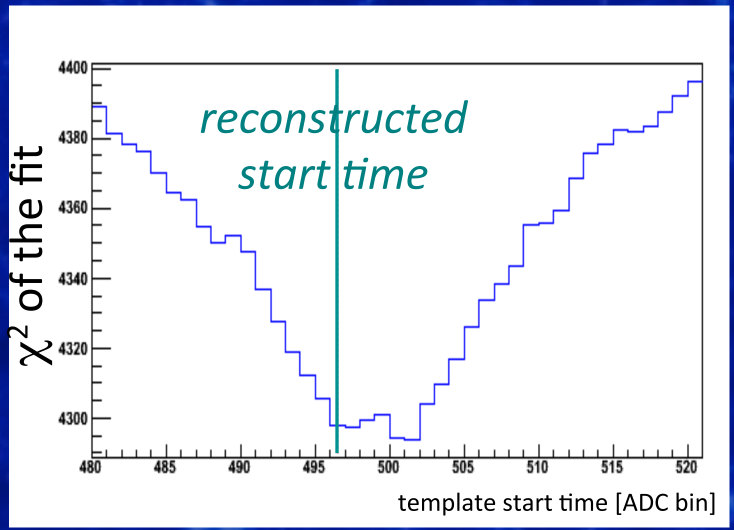
- 2 events passing all cuts
- Blinded background estimate of 0.6 ± 0.1 events

Reconstruction Checks

ionization and phonon energies look good, phonon timing looks good…



Event reconstruction algorithm did not choose the best fit



This effect is strongly correlated with the ionization energy *(affects ~1% of events with < 6 keV ionization energy)* and was mostly accounted for in the pre-unblinding leakage estimate

A more careful accounting revised the surface event leakage
from 0.6 to 0.8 events

(Note: event 1 does not appear to be affected by this issue)

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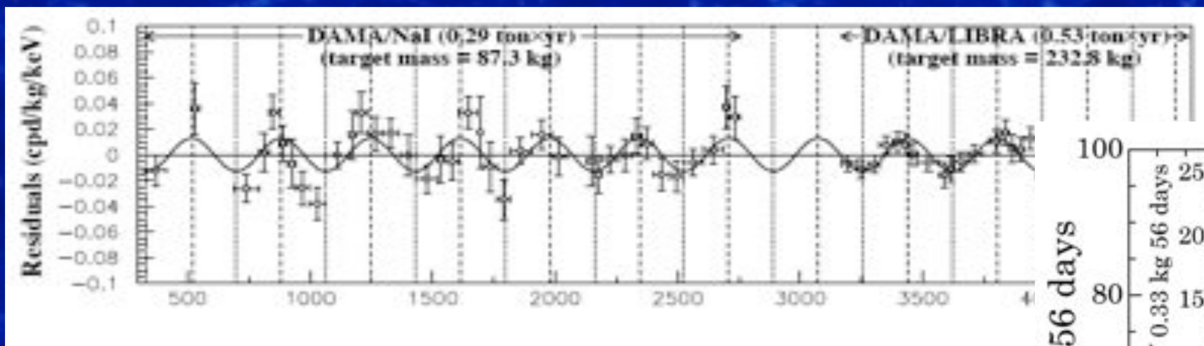
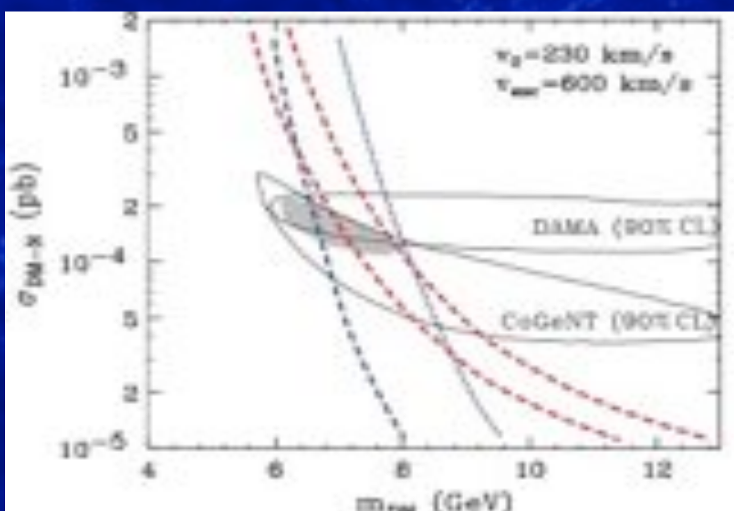
- Light Dark Matter

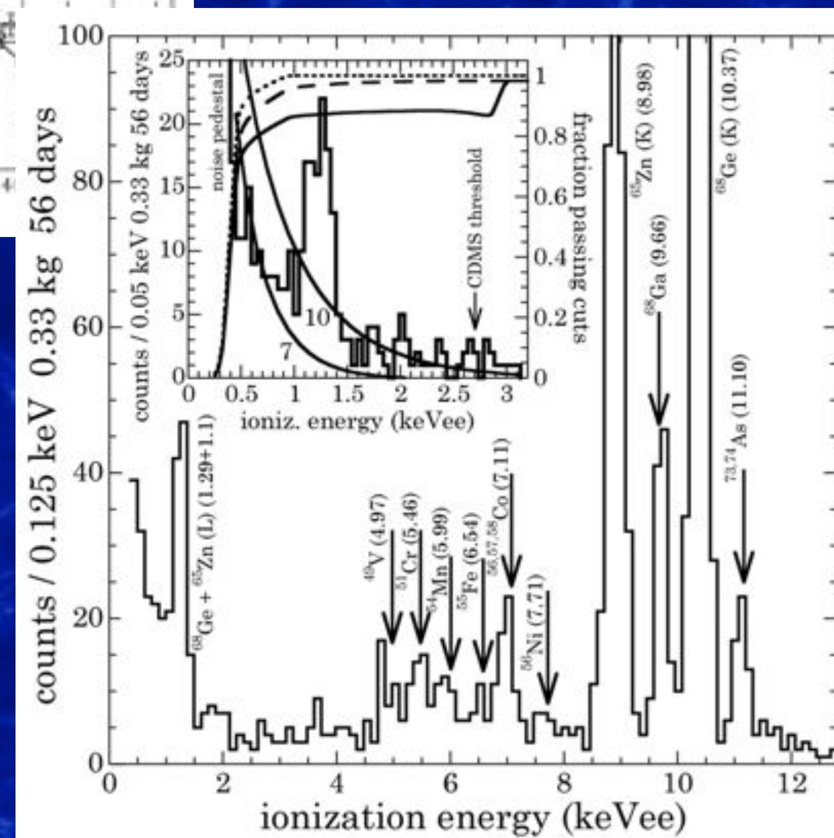
Light Dark Matter



Bernabei et al., Eur. Phys. J. C ***56*** *333 (2008)*



Hooper et al., Phys. Rev. D ***82****, 123509 (2010)*

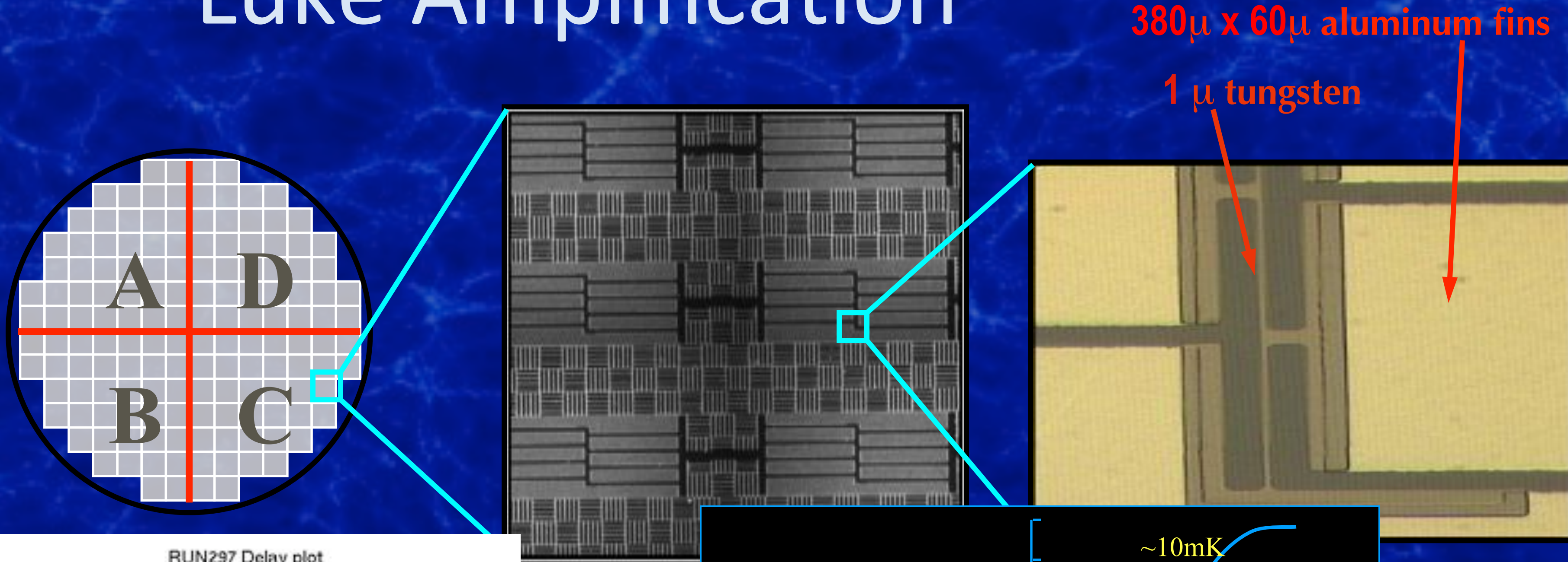


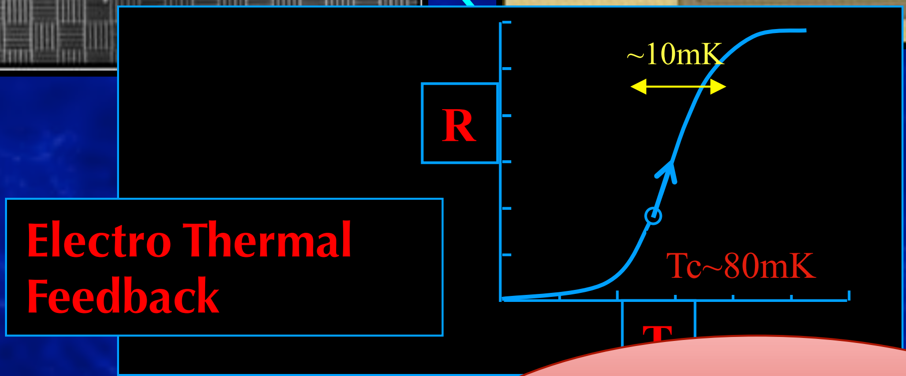
Aalseth et al., arXiv:1002.4703

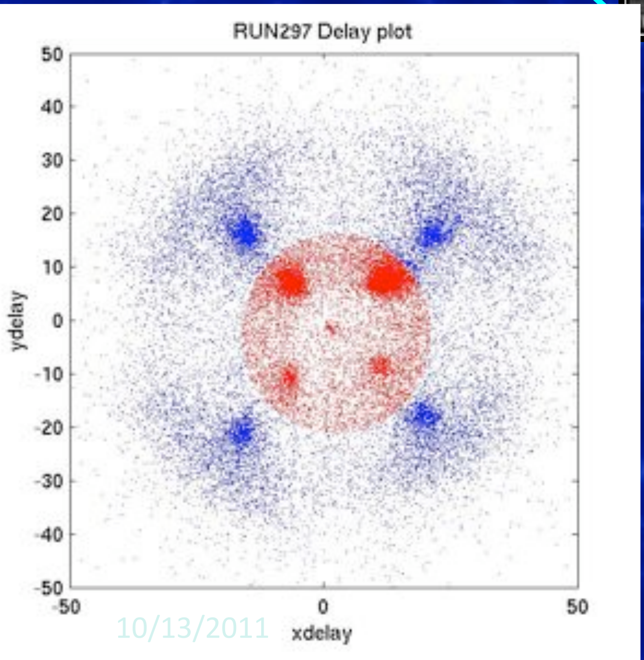
Light Dark Matter

- Recent results from DAMA/LIBRA, CoGeNT and others have been interpreted as possible evidence for elastic scatters from WIMPs with m_x~7 GeV and σ_{SI}~$1x10^{-40}$ cm^2
- Previous CDMS Ge results not sensitive to these models since thresholds were ~10 keV (to maintain expected backgrounds <1 event)
- Can lower thresholds significantly at cost of higher backgrounds

Luke Amplification





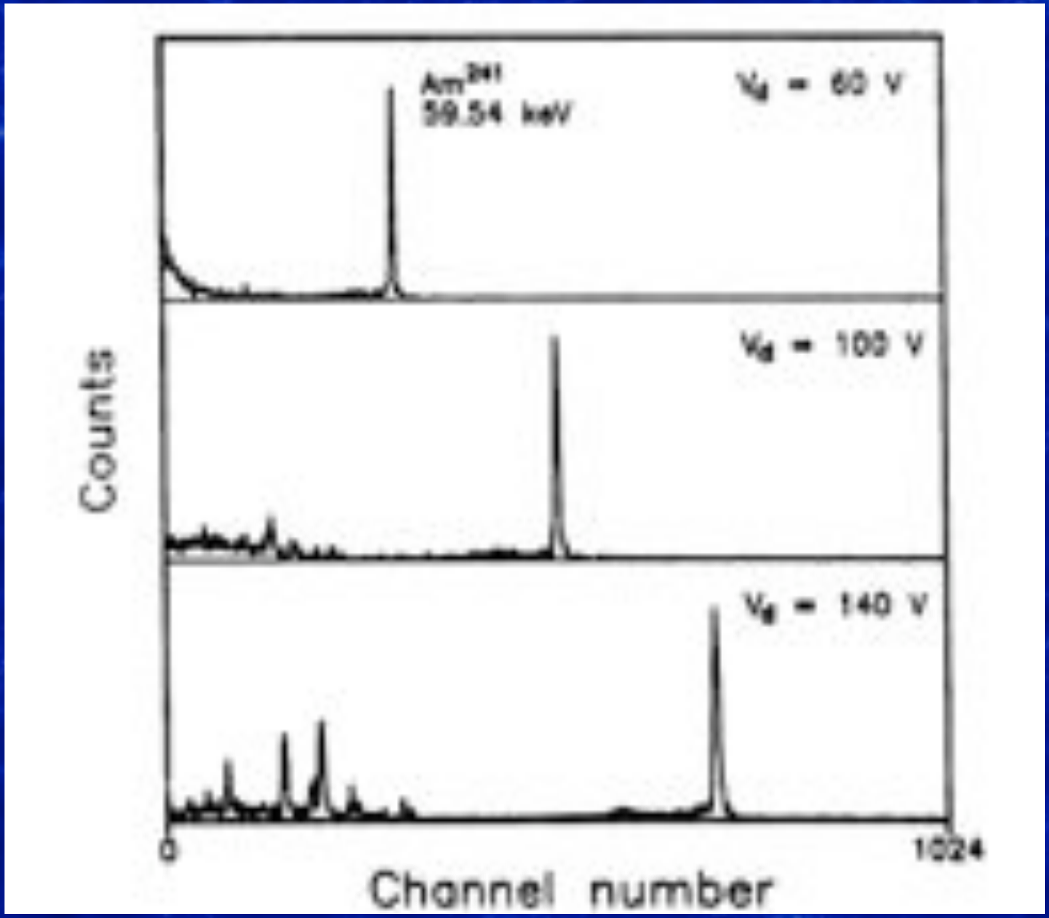


$$E_{phonon} = E_{reco} + V \times E_{ionization}/\varepsilon$$

Luke Amplification

Exponential is the most generic spectrum, especially near the electronic noise of detectors

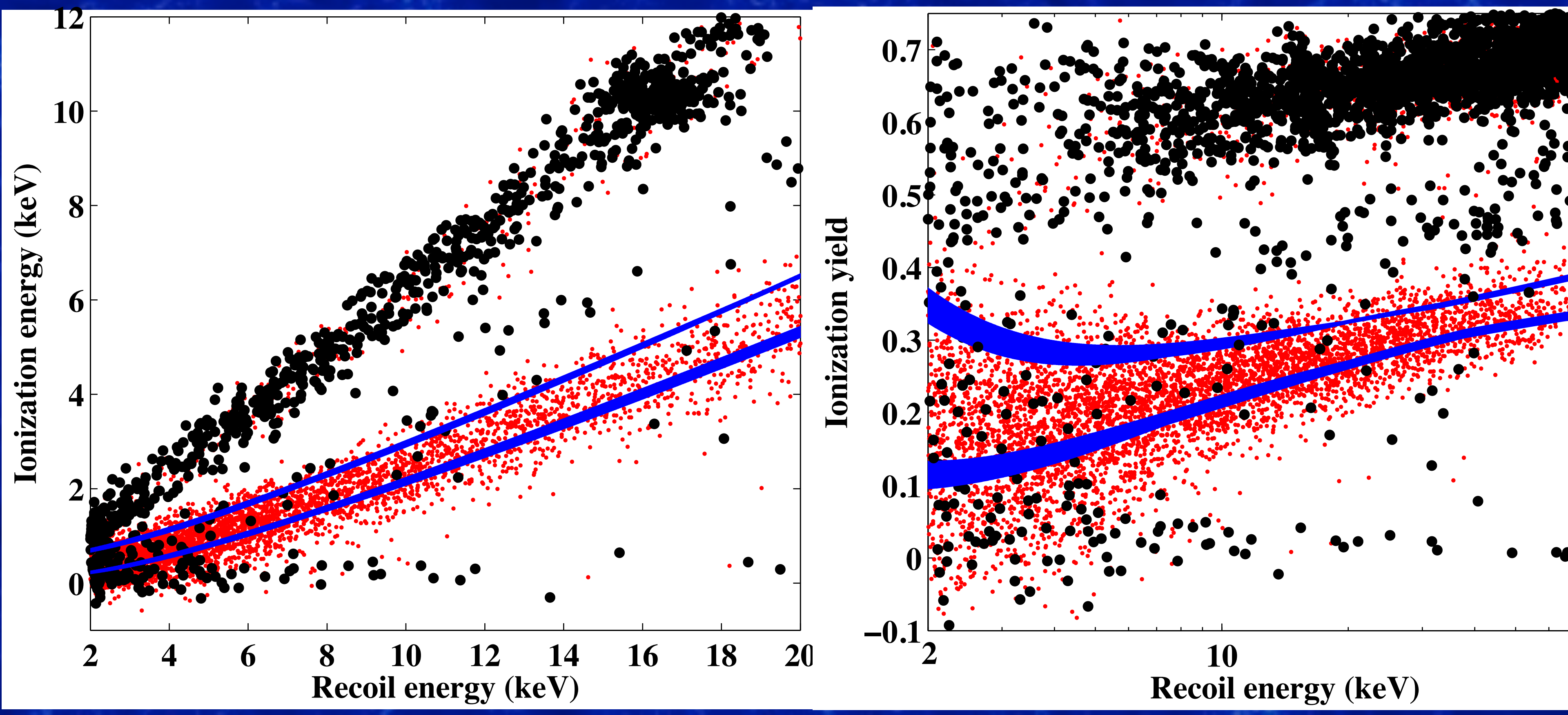
Good signal to noise is an important ingredient for understanding a dark matter signal



P.N. Luke et al., NIM A289, 406 (1990)

Low Energy Events in CDMS

- At low energies the discrimination between nuclear and electron recoil worsens



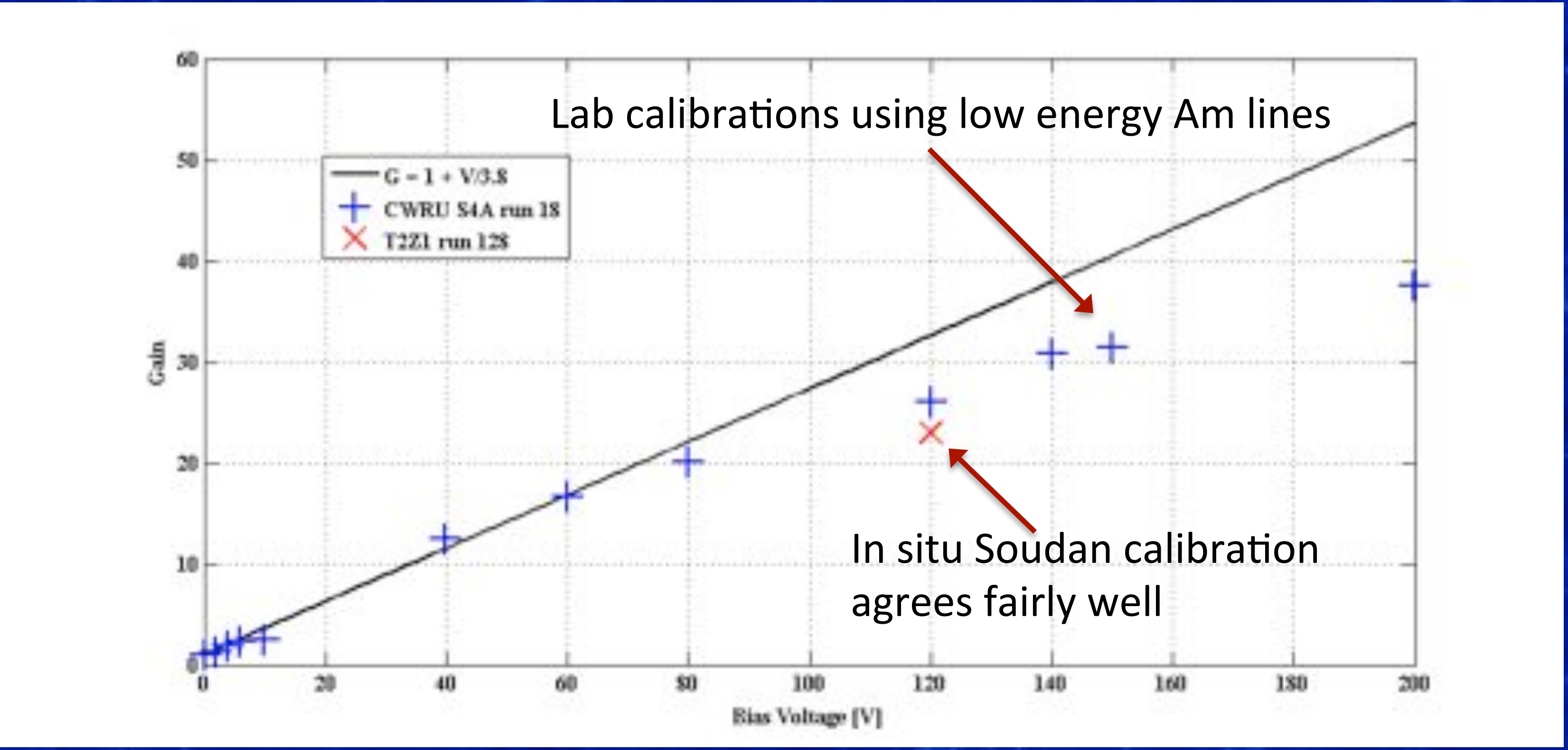
Luke Amplification

- First Suggestion
  - P.N. Luke, J.Appl.Phys 64, 12 (1988)
  - P.N. Luke et al., NIM A289, 406 (1990)
- Investigation for dark matter
  - N.J.C. Spooner et al., Phys. Lett. B278, 382 (1992)
- Photon detection for CRESST
  - M. Stark et al., NIM A545, 738 (2005)
- Using CDMS detectors for coherent neutrino elastic scattering
  - D.S. Akerib et al., NIM A520, 163 (2004)

Turning it up to 11

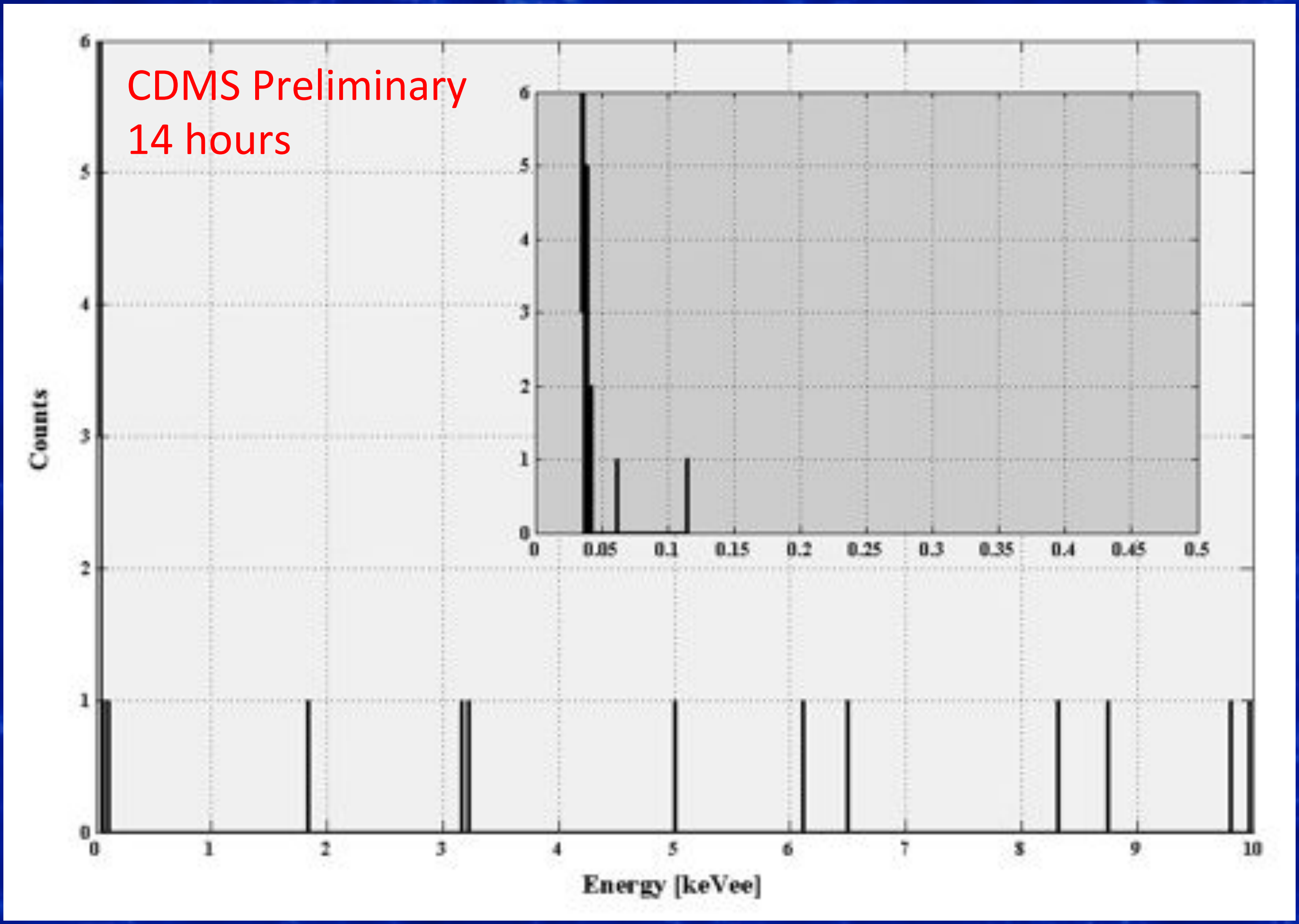
- CDMS electronics max bias is 10V, Luke gain of 2
- Parasitic investigation during CDMS

Luke Gains



- Gain deviates from theory, coincident with turn on of field emission

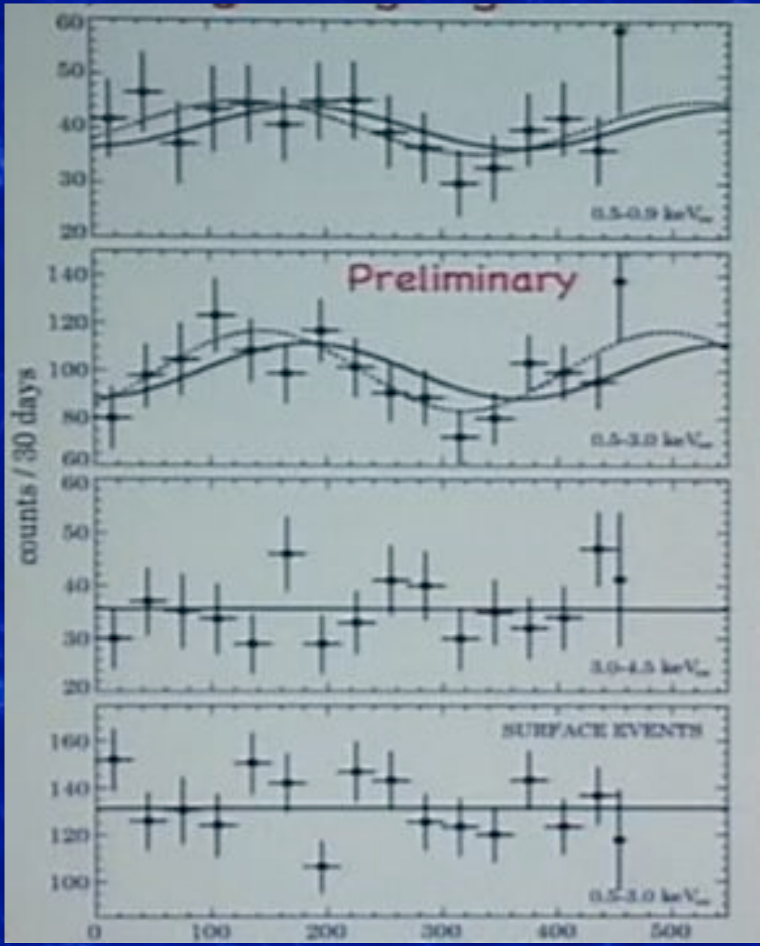
CDMS Luke amplification



- Signal gain of 22 with ~50% increase in noise
- 50 eV threshold in Soudan (12 eh pairs)

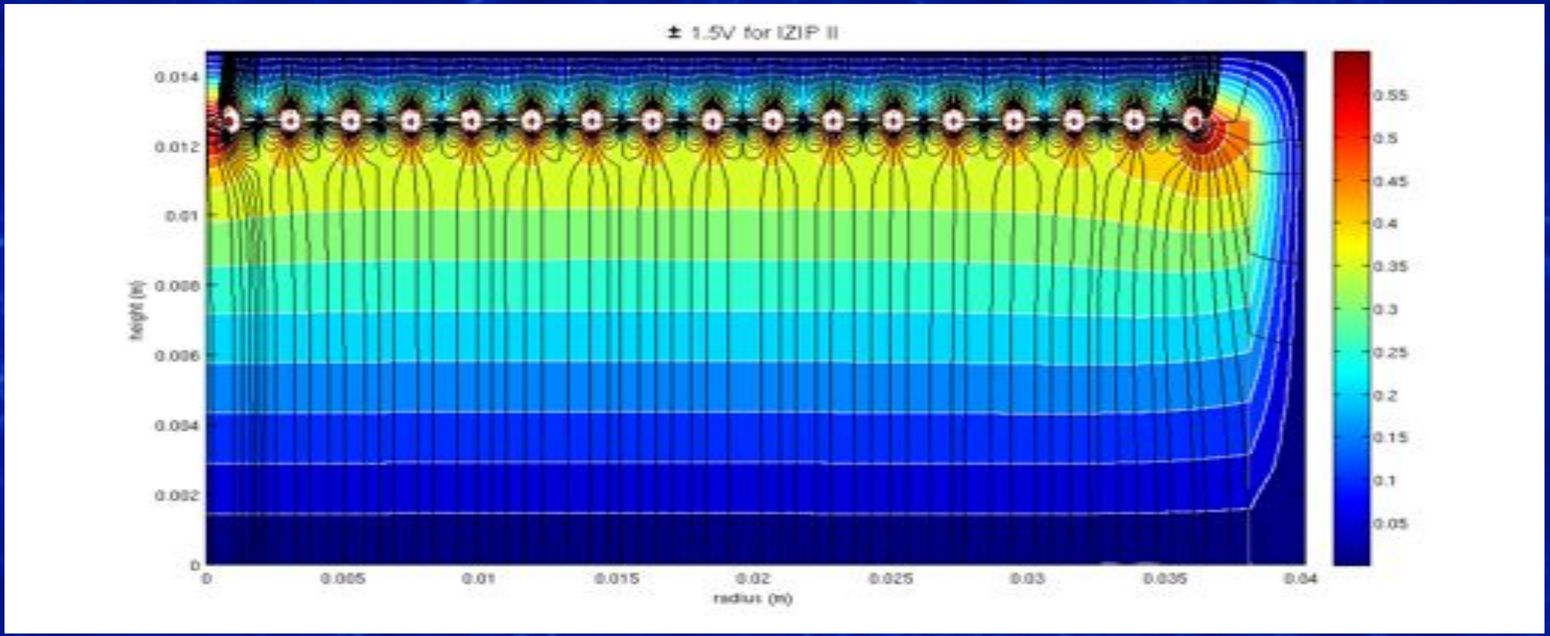
CoGeNT Annual Modulation

- The situation has become even more interesting
- The CoGeNT collaboration reported a posible annual modulation signal at the April APS meeting
- 2.8 sigma significance



SuperCDMS Technology Breakthrough

- New symmetric detectors (iZIP) have demonstrated a background rejection improvement of more than an order of magnitude (ton scale CDMS style experiment now feasible)
- Trial run in Soudan facility with a 10 kg payload (X5 sensitivity)

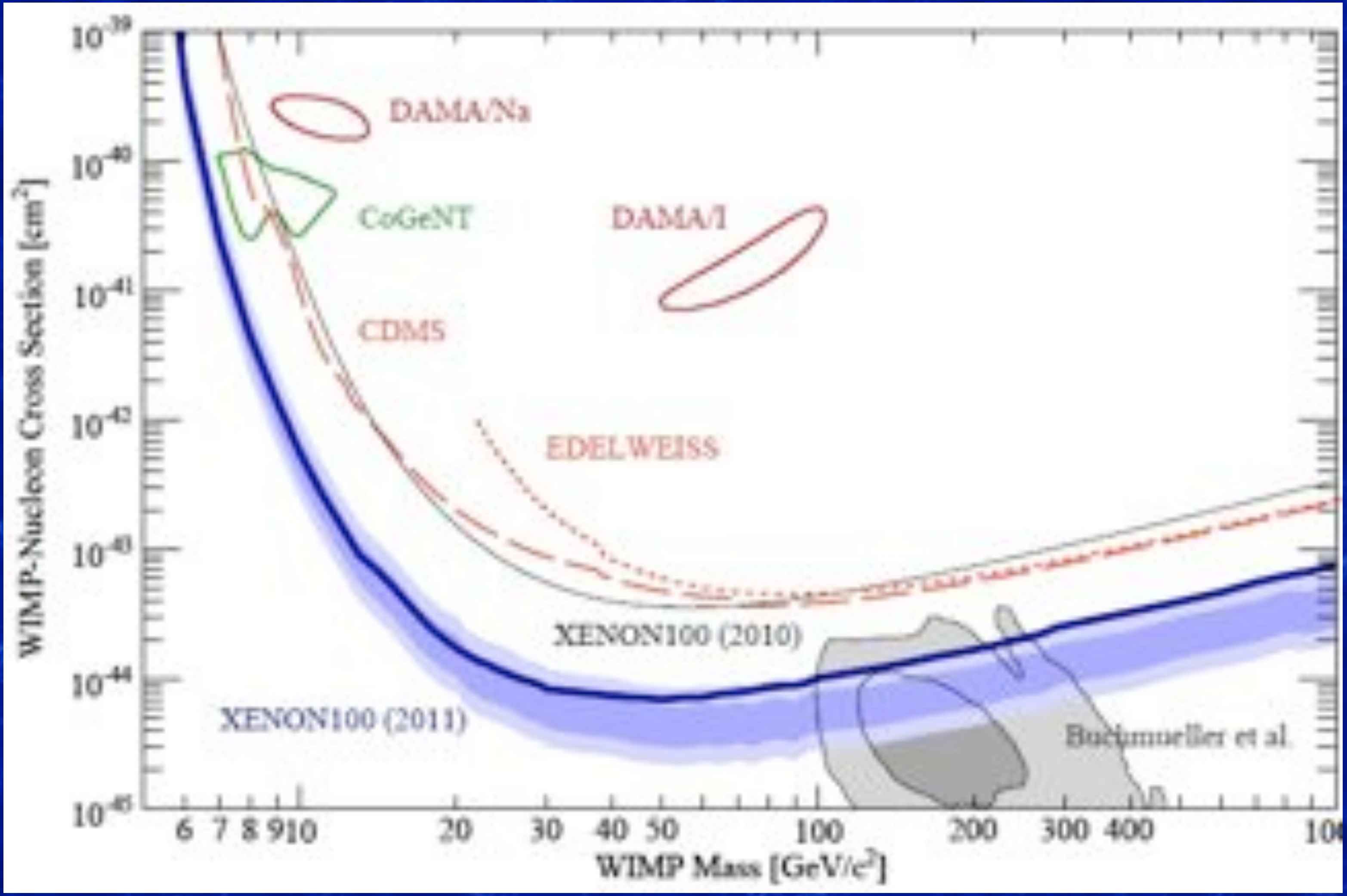


SuperCDMS Delay

- 10 kg experiment starts August
- Impact minimal but some enginering work delayed

Backup

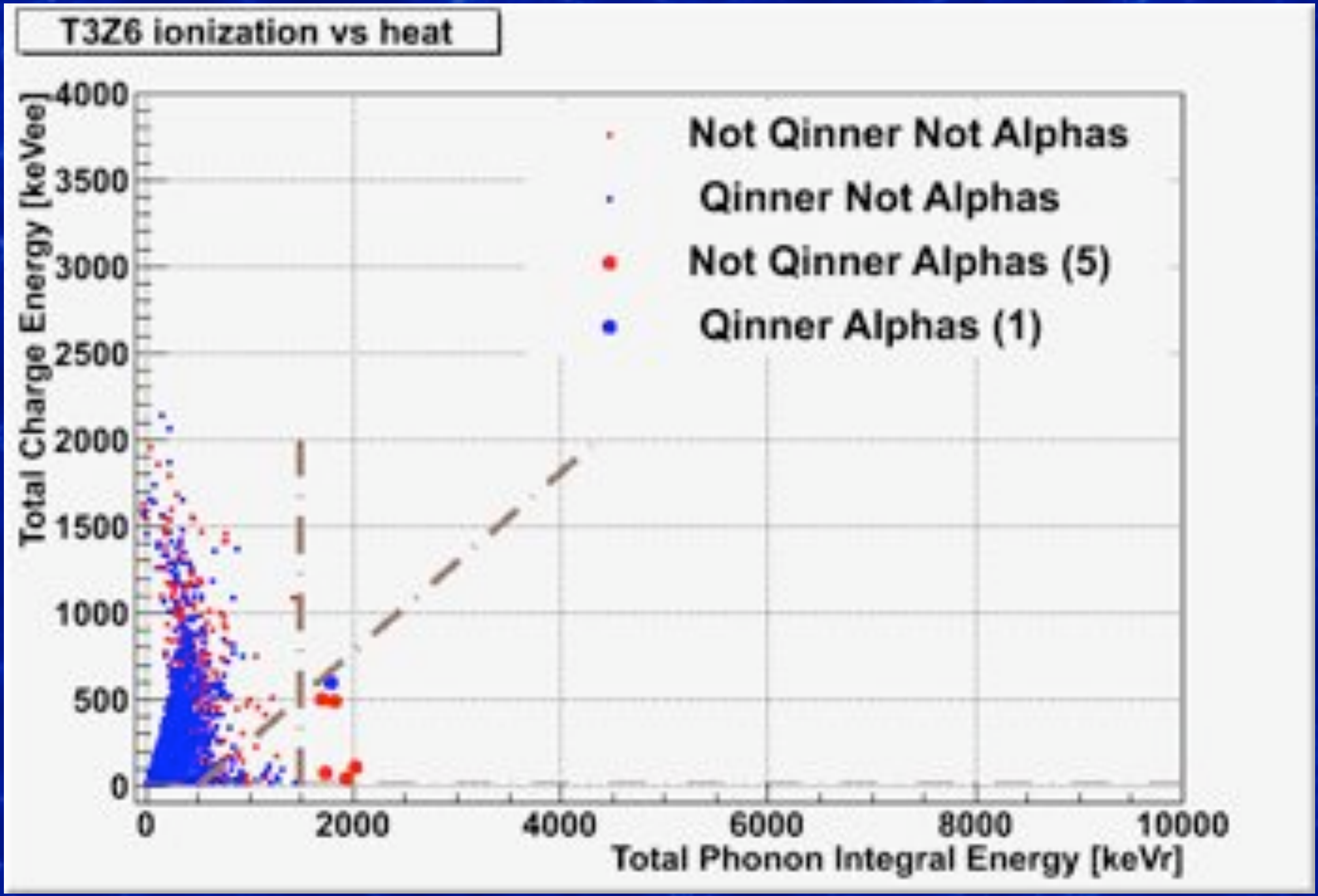
Xenon-100 Results



Low threshold sensitivity

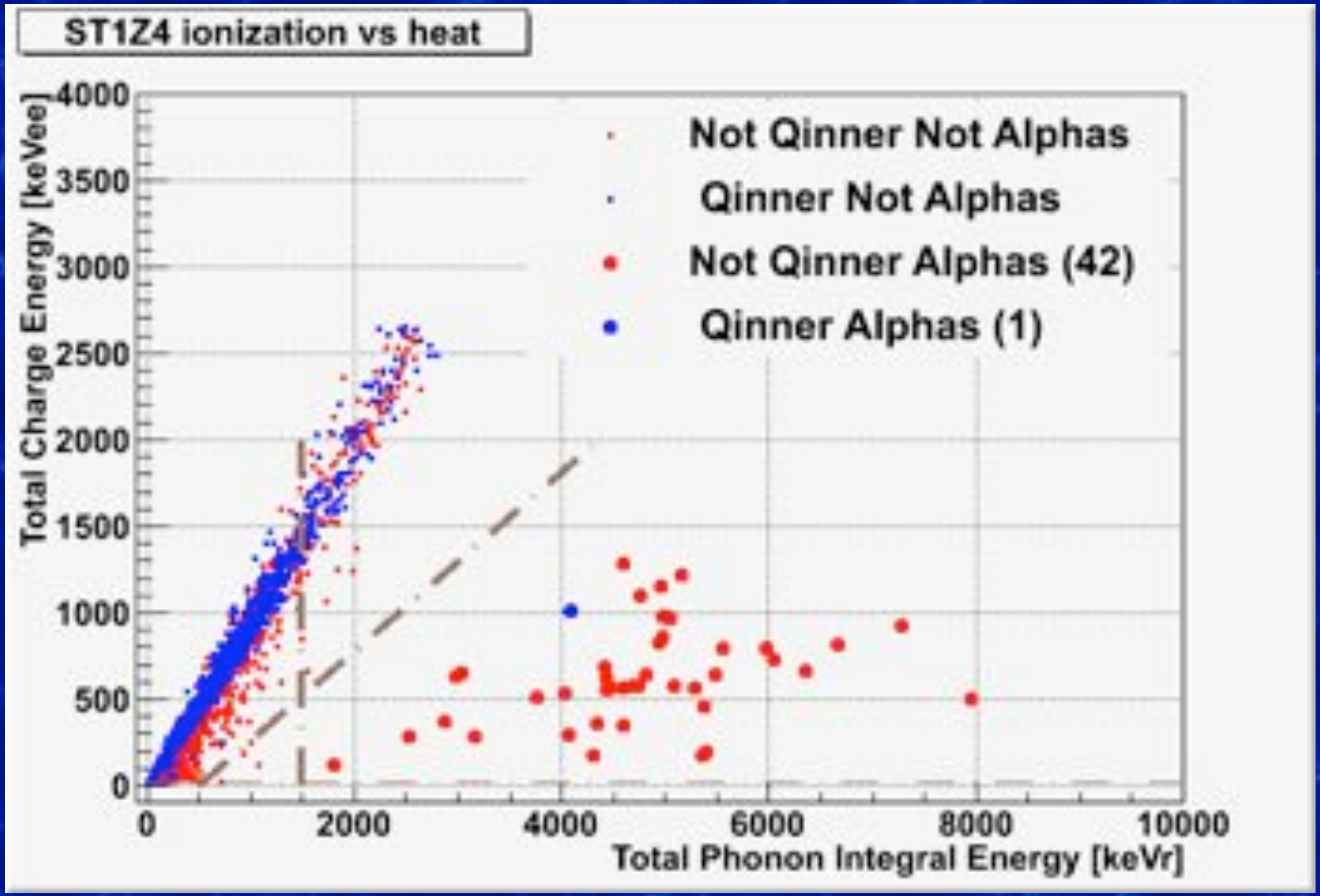
- Low threshold sensitivity is limited by backgrounds
- Understanding the backgrounds is now the way to make progress with CDMS
- ~2 months of data taken with high voltage (14 hours shown here)
- Few days of Germanium data taken

CDMS Phonon Non-Linearity



- CDMS-II Detectors can have strong non-linearity above ~few 100s keV

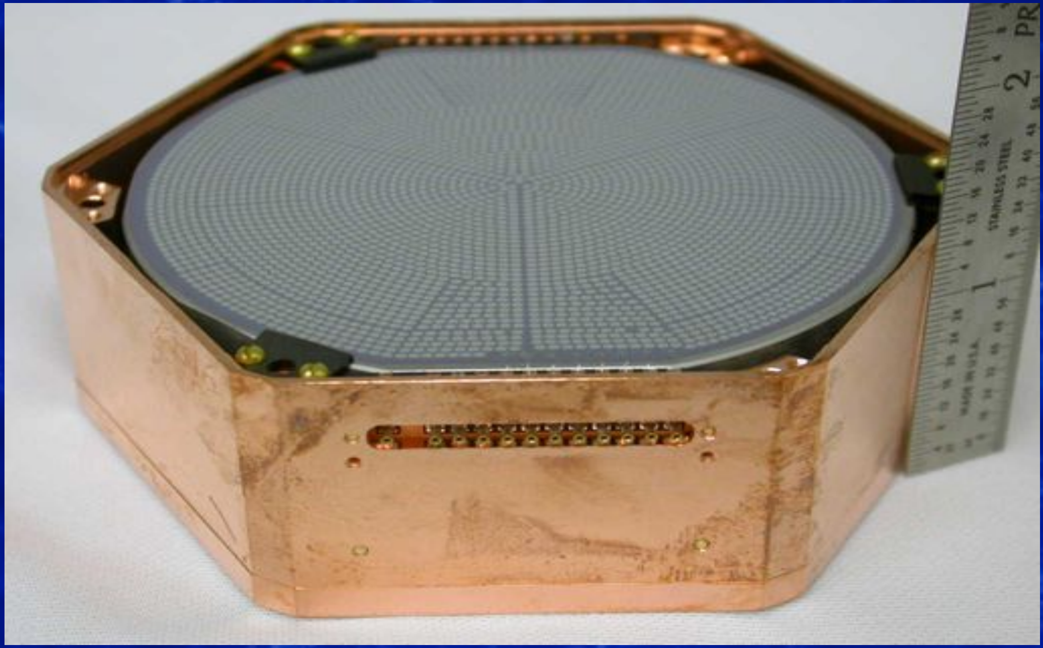
SuperCDMS Phonon Linearity



- New SuperCDMS detectors exhibit much better linearity

SuperCDMS Luke Amplification Advantages

- Better linearity
- Germanium has low energy lines for calibration
- 2.5X Thicker = 2.5X less E
  - Field emission at higher V
  - Breakdown at higher V



Outline

- Dark Matter Problem
- Cryogenic Dark Matter Search
- Chicagoland Observatory for Underground Particle Physics
- Summary

The COUPP Collaboration

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Fermi National Accelerator Laboratory

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COUPP Bubble Chamber Program

- Take long runs with smaller chambers to understand backgrounds, operations, and for research and development while developing and commissioning an order of magnitude larger chamber

Test tube
(U Chicago)

Science **319**:933-936 (2008)

COUPP 2kg

Latest Results
To appear in PRL

COUPP 4kg

Stay Tuned

Ton Scale?

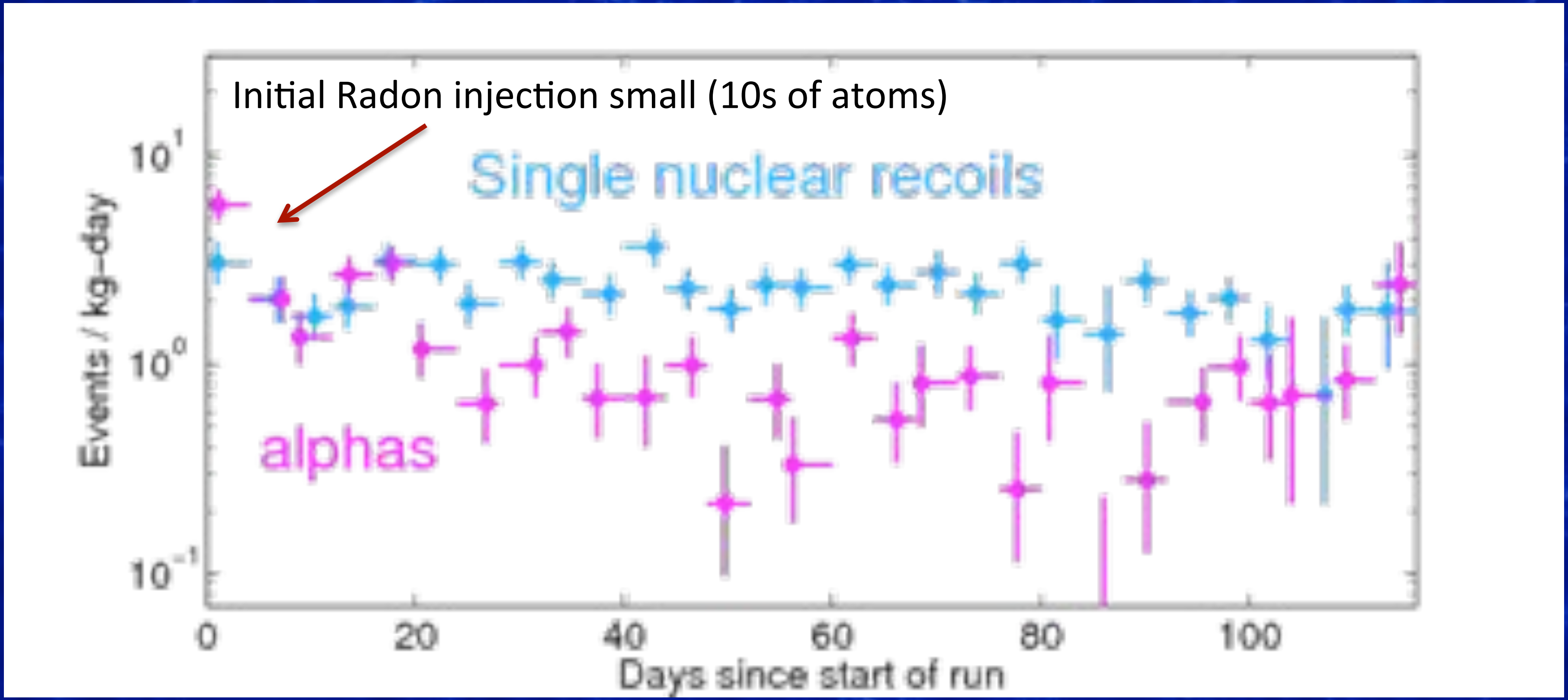
COUPP 60kg

COUPP 4 kg Bubble Chamber

- 2L synthetic silica bubble chamber
- Filled with 4 kg CF_3I
- 300 feet underground at Fermilab
- Surrounded by a liquid scintillator cosmic ray veto

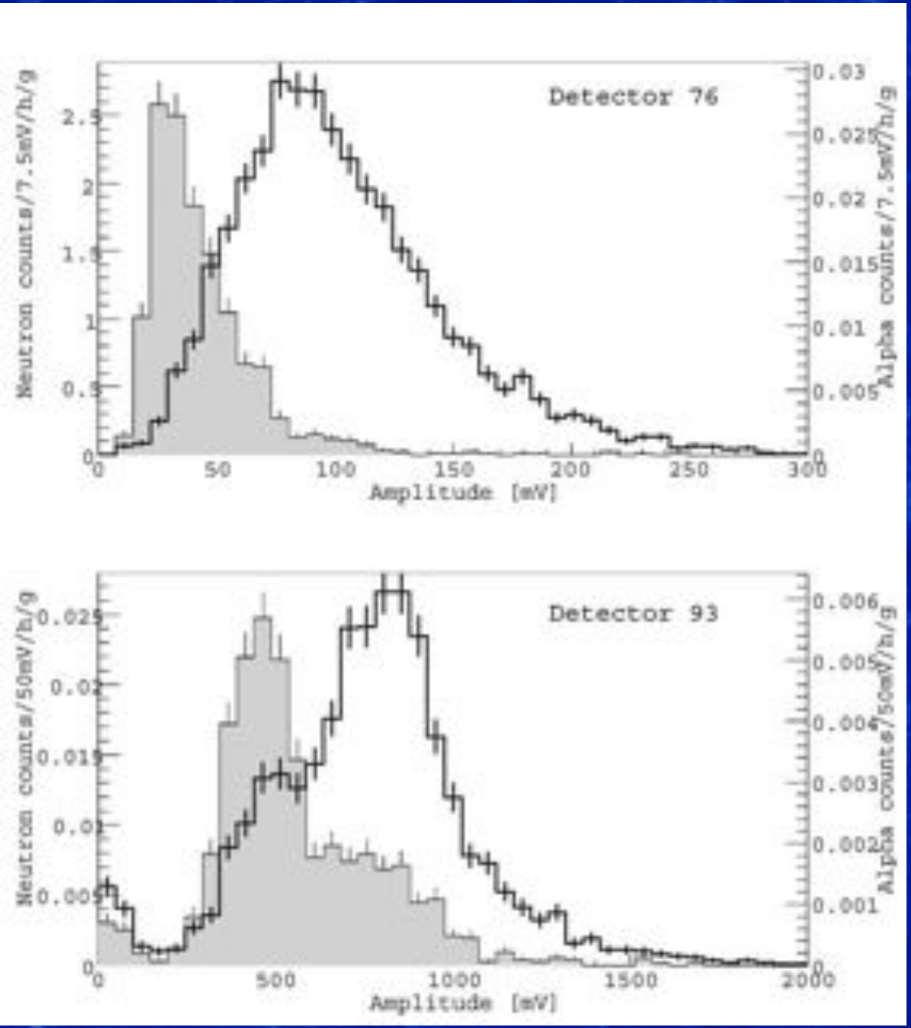
4 kg Alpha Rate Reduction

- Initial Radon injection ~10X lower due to improved fluid transfer
- About ~100X reduction in equilibrium alpha rate with improved selection of materials



Acoustic Discrimination

- PICASSO (a search for dark matter with superheated freon droplets) reports alpha decays are louder than nuclear recoils

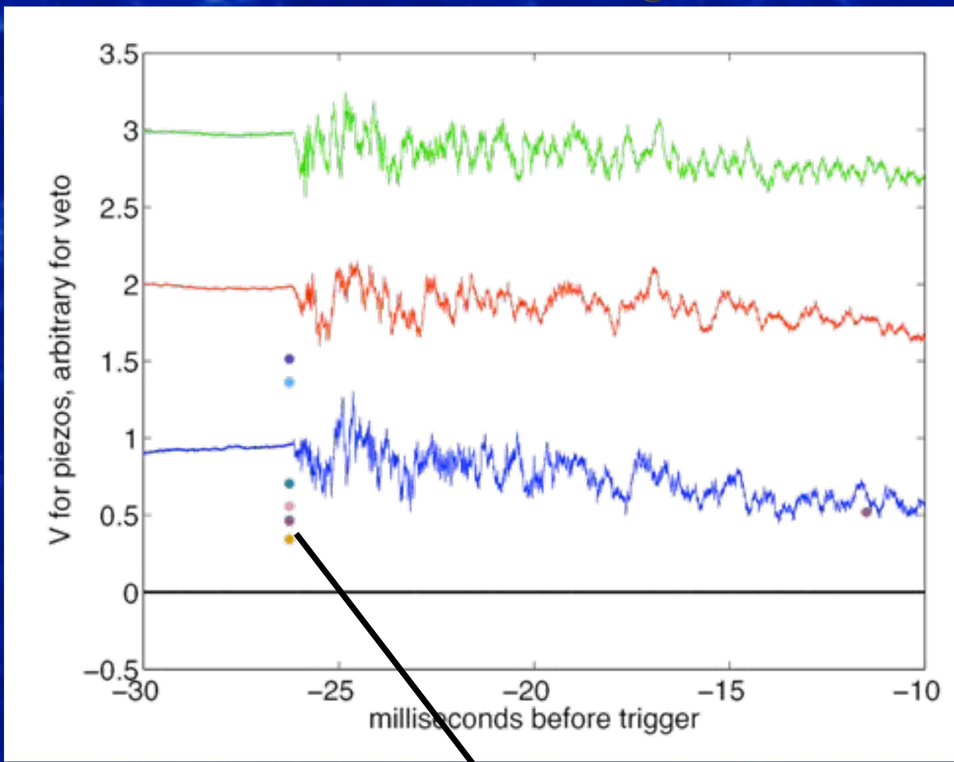


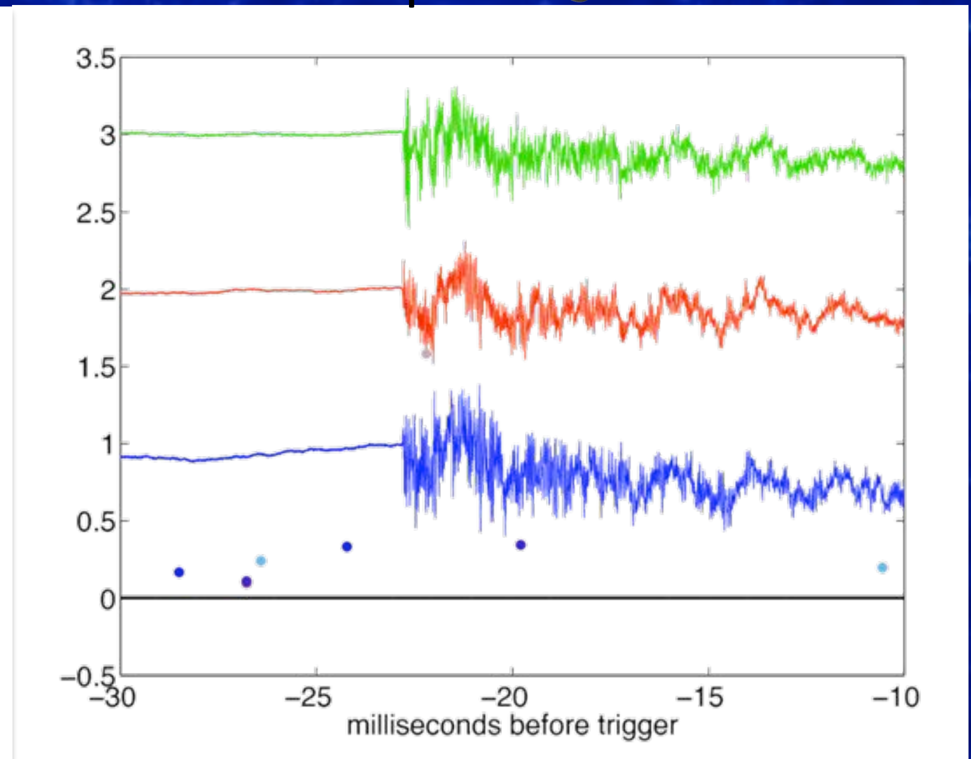
New Journal of Physics arXiv:0807.1536

Acoustic Signatures, time domain

Neutron

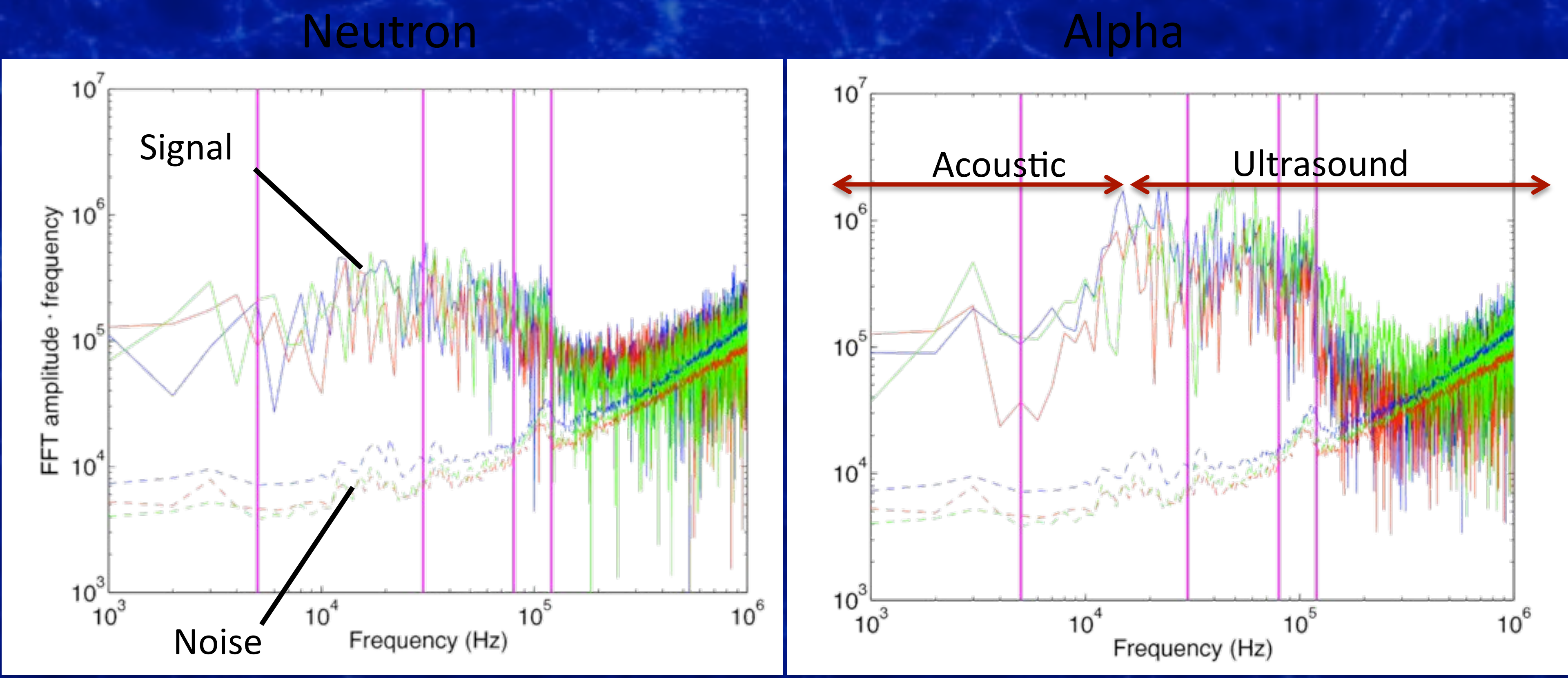
Alpha





cosmic ray veto individual PMT hits

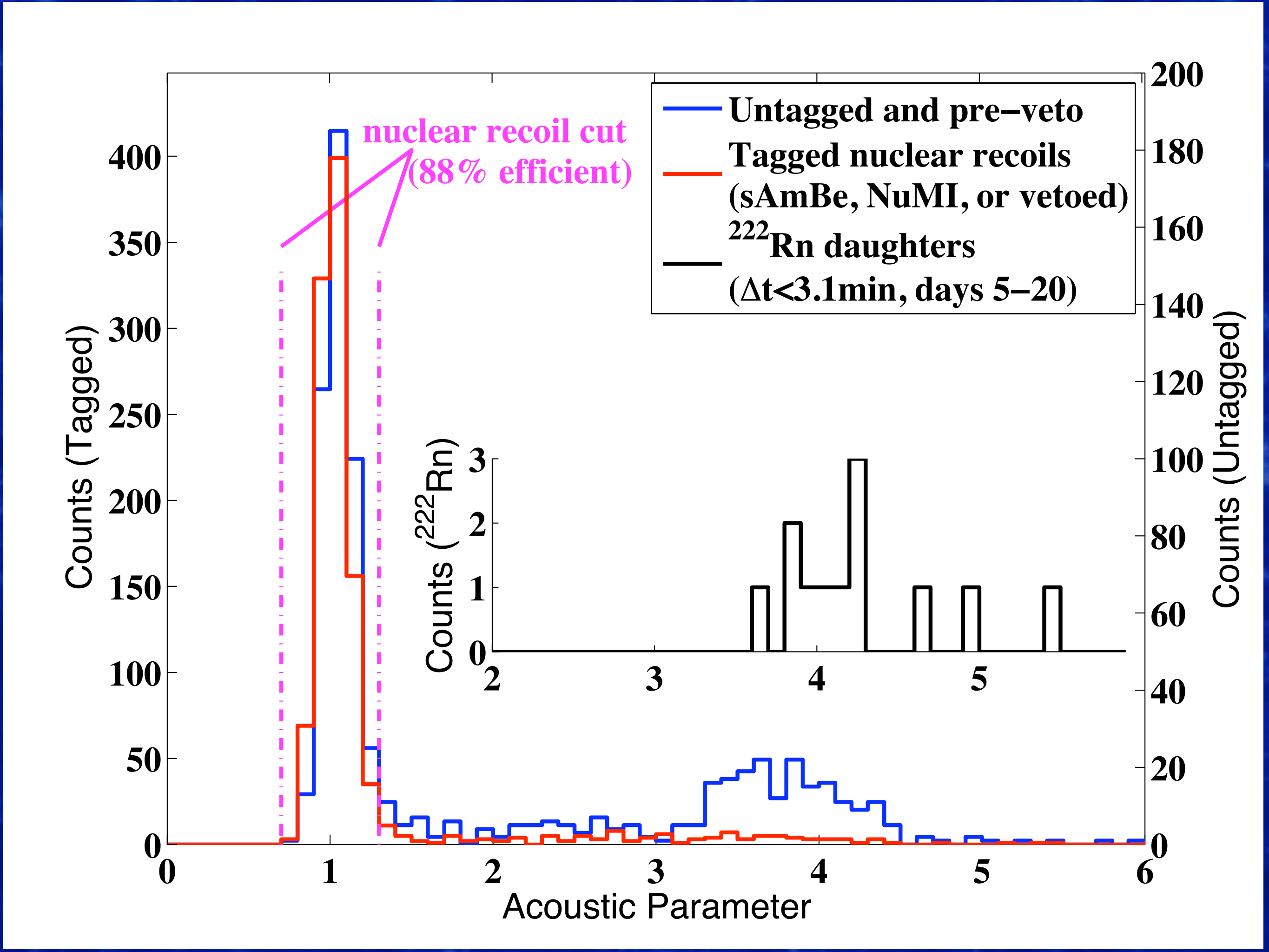
Frequency Domain



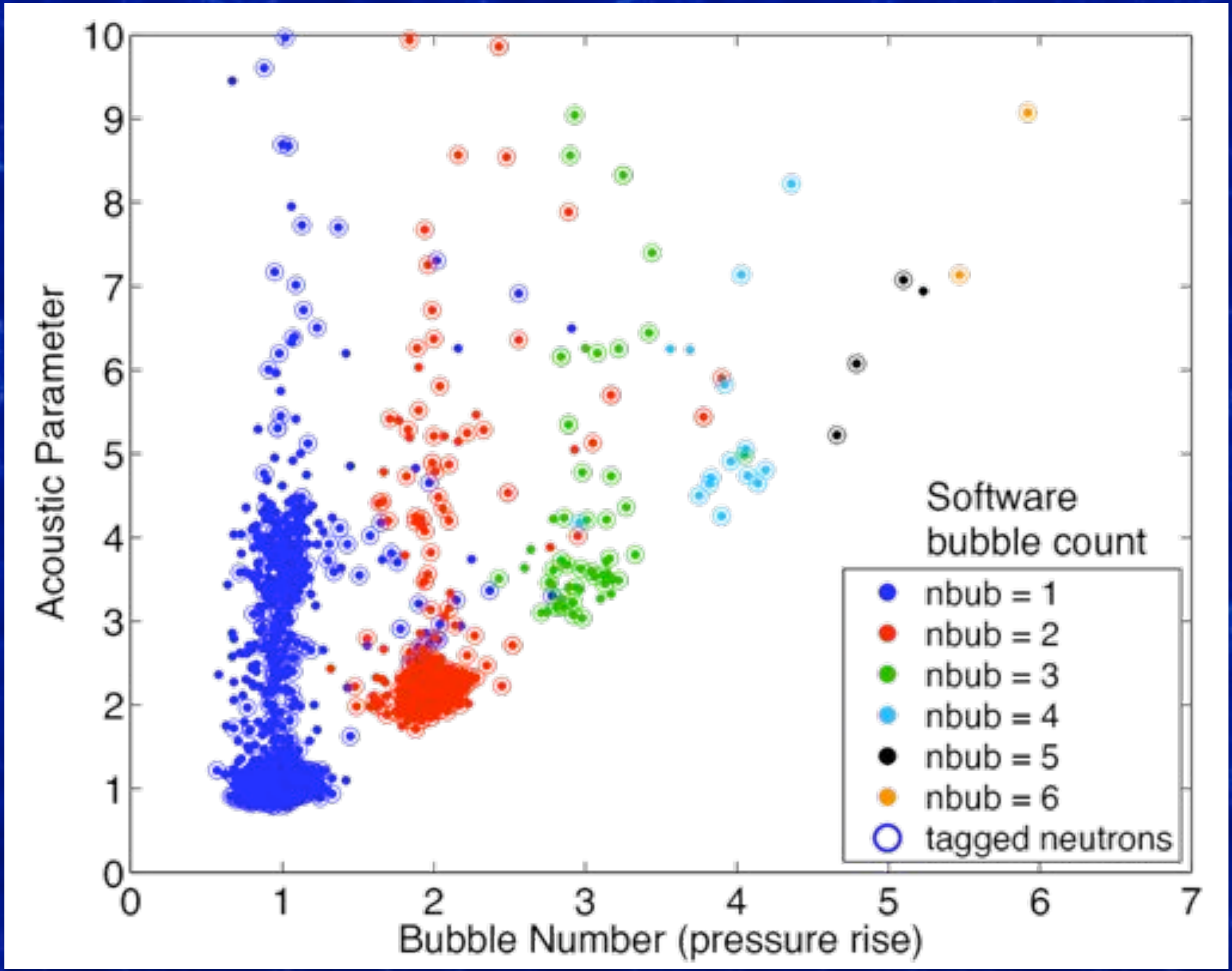
- Analysis separates power in a few observed resonances
- Acoustic power is calibrated w.r.t. bubble position

Acoustic Parameter

- $(\text{Amp} \bullet \omega)^2$ (Normalized and position-corrected for each freq-bin)
- Measure of acoustic energy deposited in chamber
- Alphas are louder than neutrons
- ~200 well separated alpha events

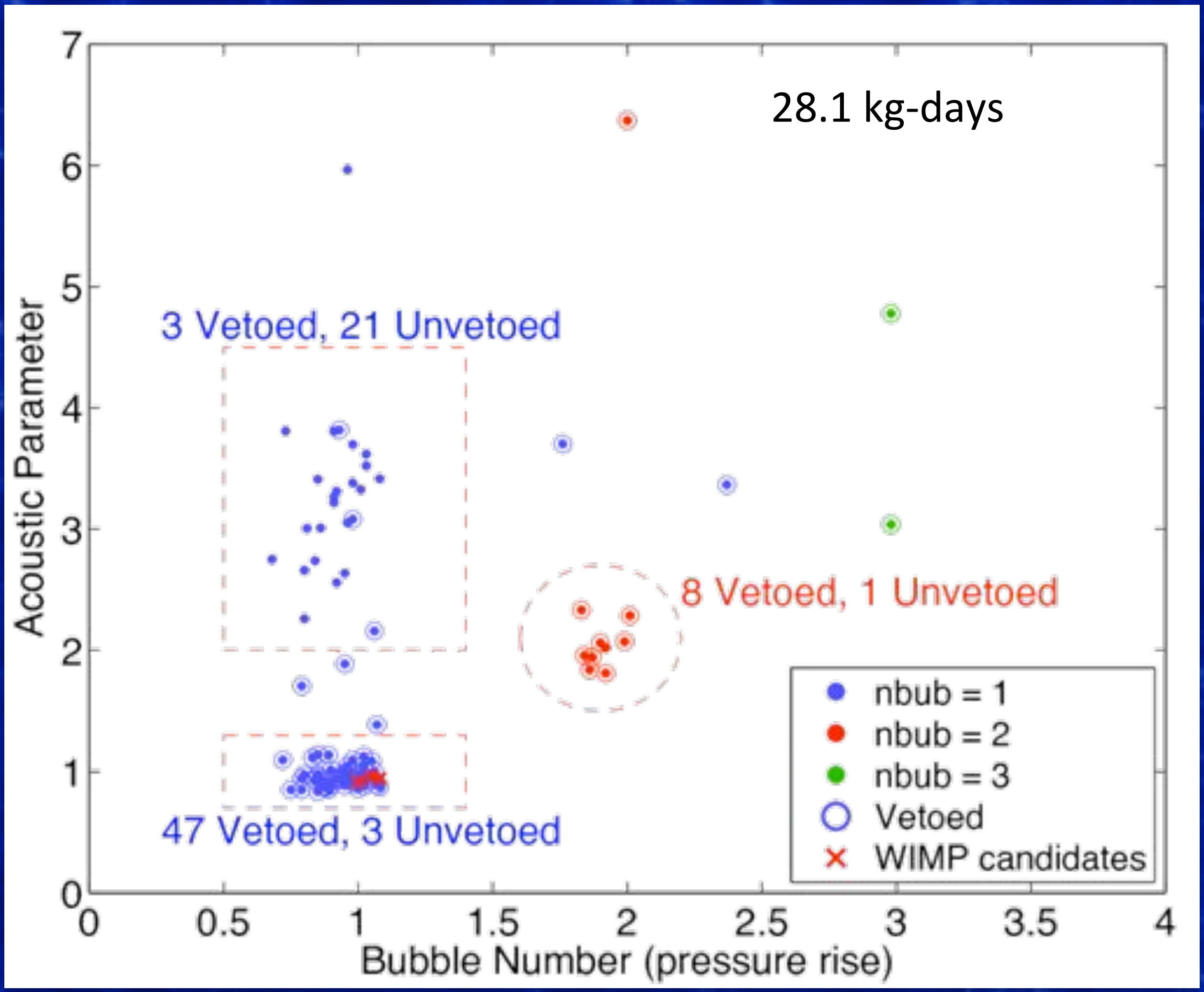


Counting Bubbles



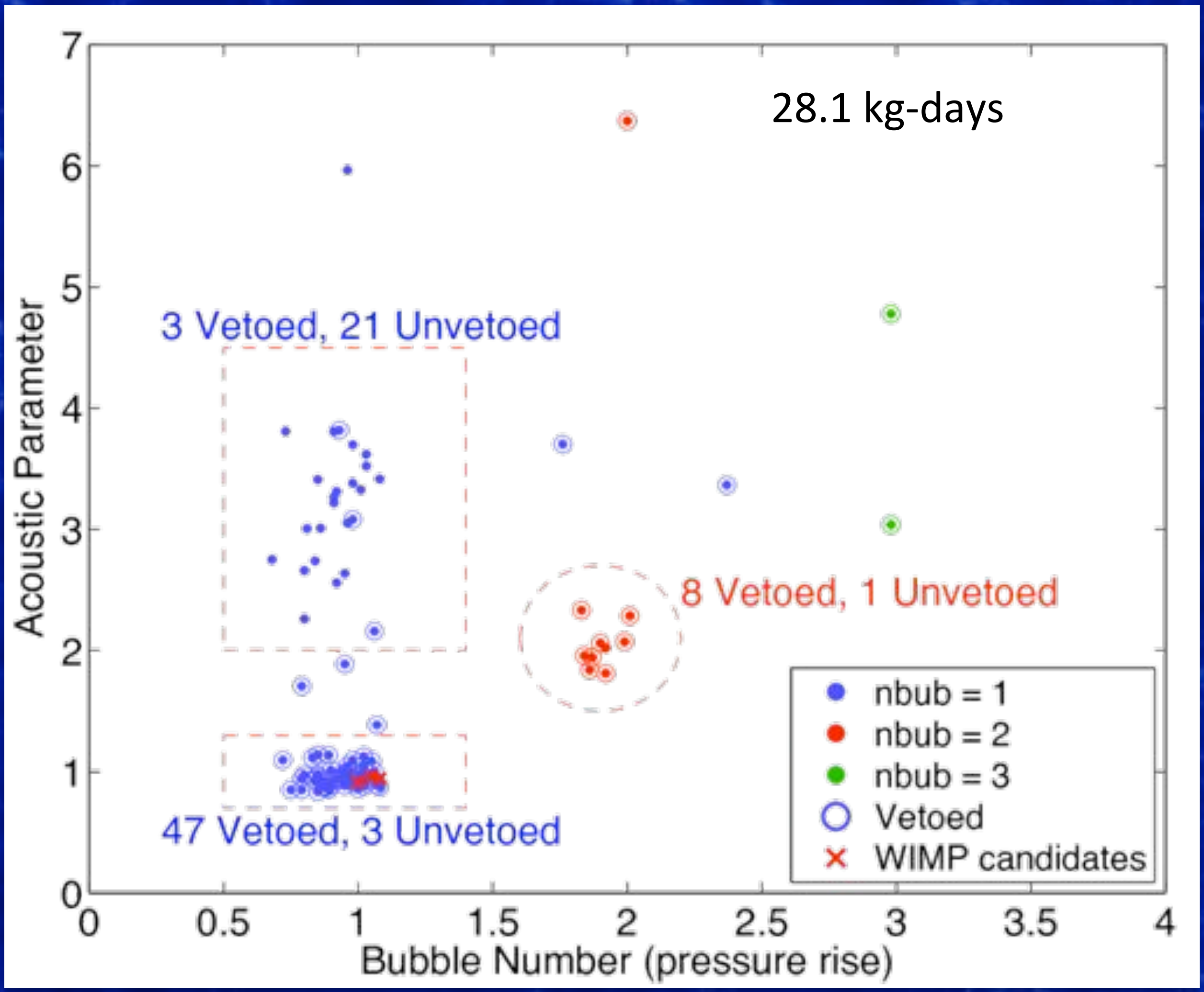
- 3 Methods of counting bubbles
  - Camera Images
  - Pressure Rise
  - Acoustic Parameter
- Acoustic Parameter (AP) scales with # of bubbles
- No tails at low AP
- 291 kg-days, mostly before veto installation

Candidate Events



- 3 Events Pass All Cuts
  - Alphas?
  - Neutrons?
  - WIMPs?
- Note 1 double scatter leaks through veto
- Limited by cosmic radiation

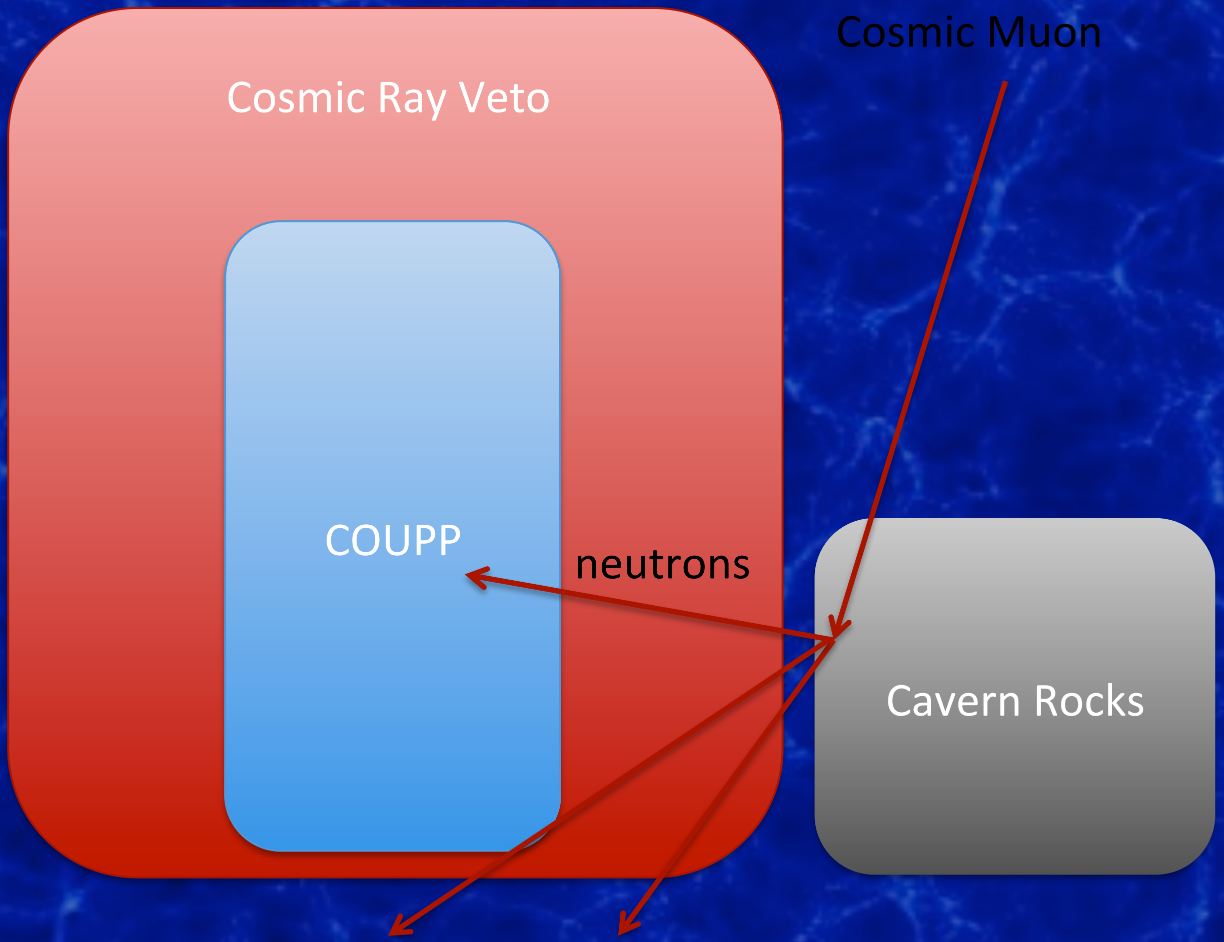
Candidate Events



- Taking the 3 unvetoed events as alphas
- Alpha rejection ~75% at 90% confidence level
- Populations are well separated
- 1 double scatter, so events are certainly neutrons

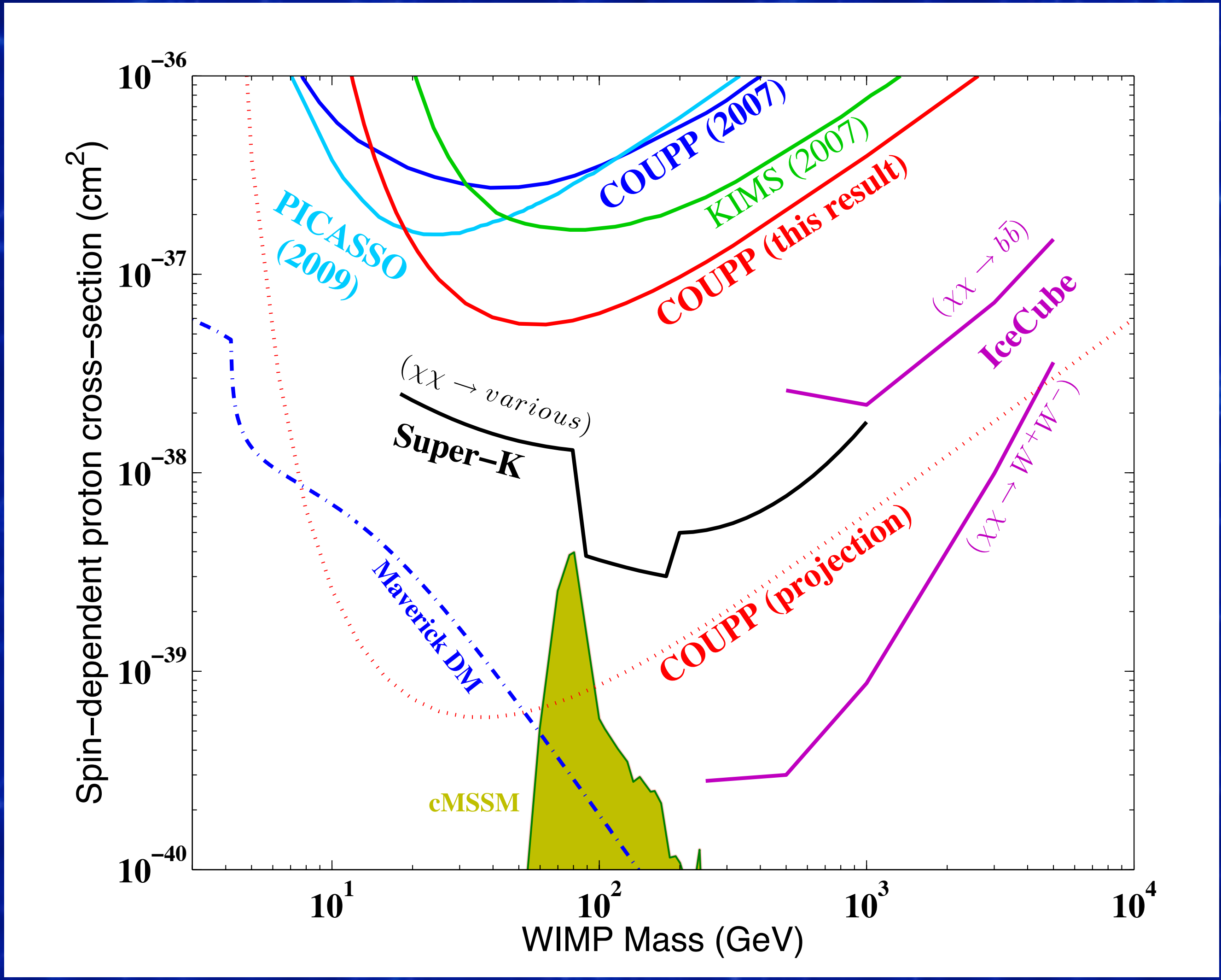
Punch Through Neutrons

- Neutron-nucleus elastic scattering "neutrons"
- From cosmic muons
- Created outside the shield
- Penetrating the shield



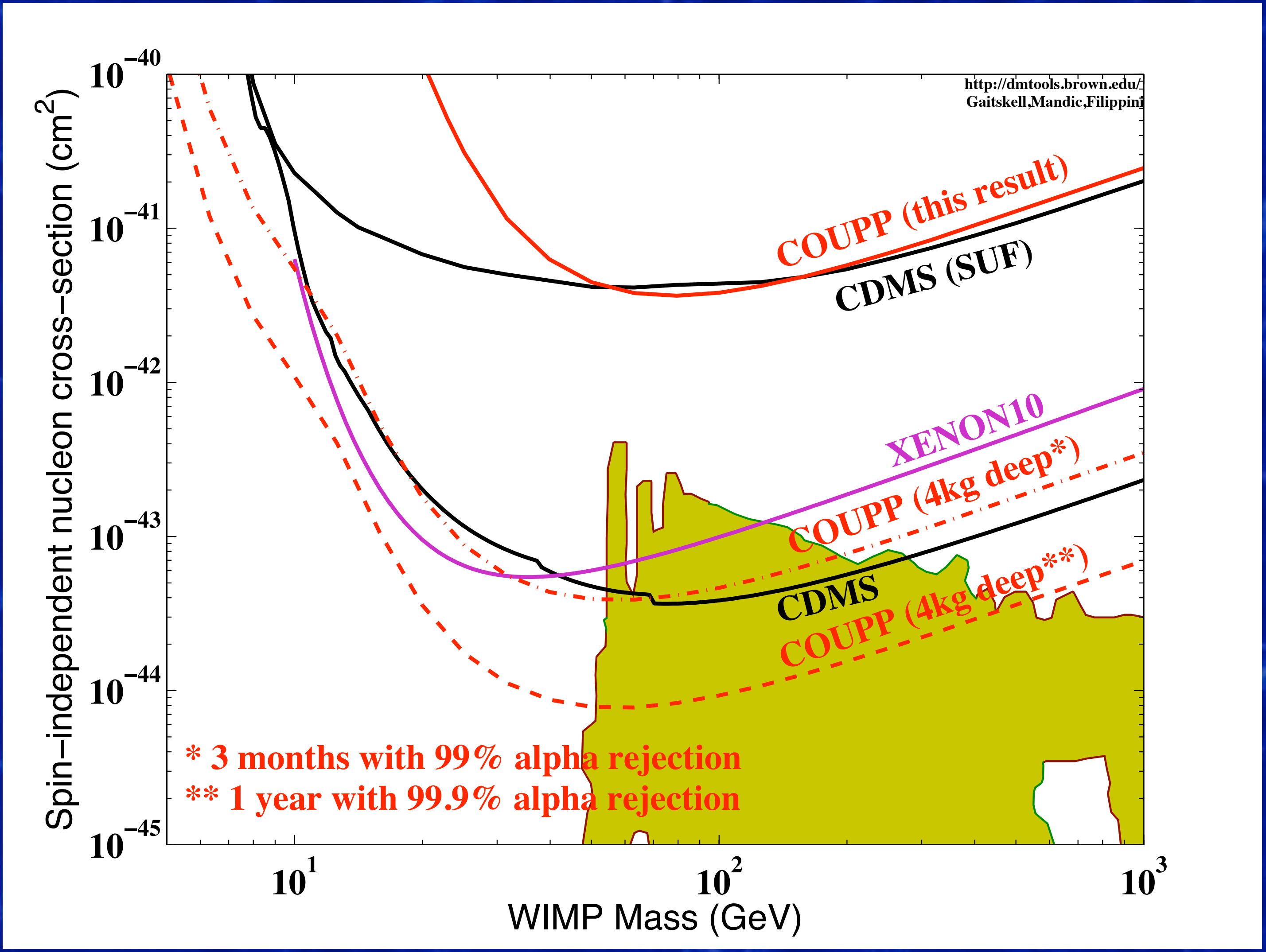
COUPP Dark Matter Limits

- Taking the 3 events to be WIMP scatters
- Constrains WIMP-proton spin-dependent scattering



To appear in PRL

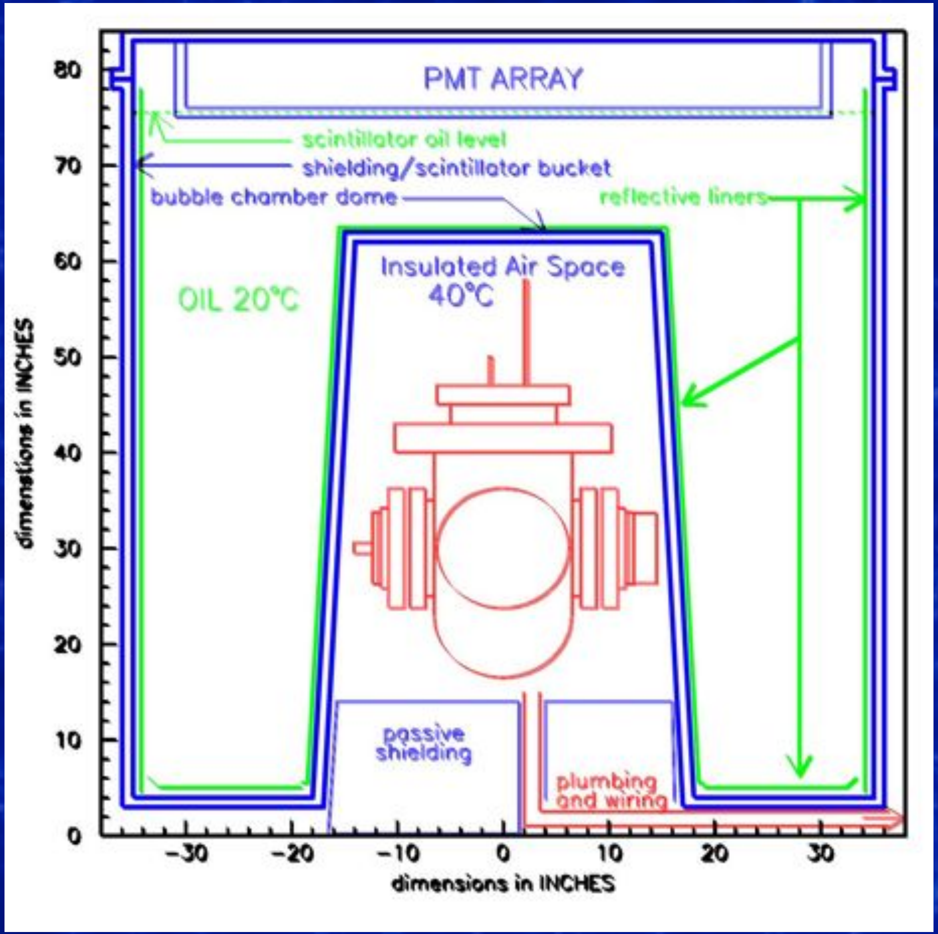
New Dark Matter Limits



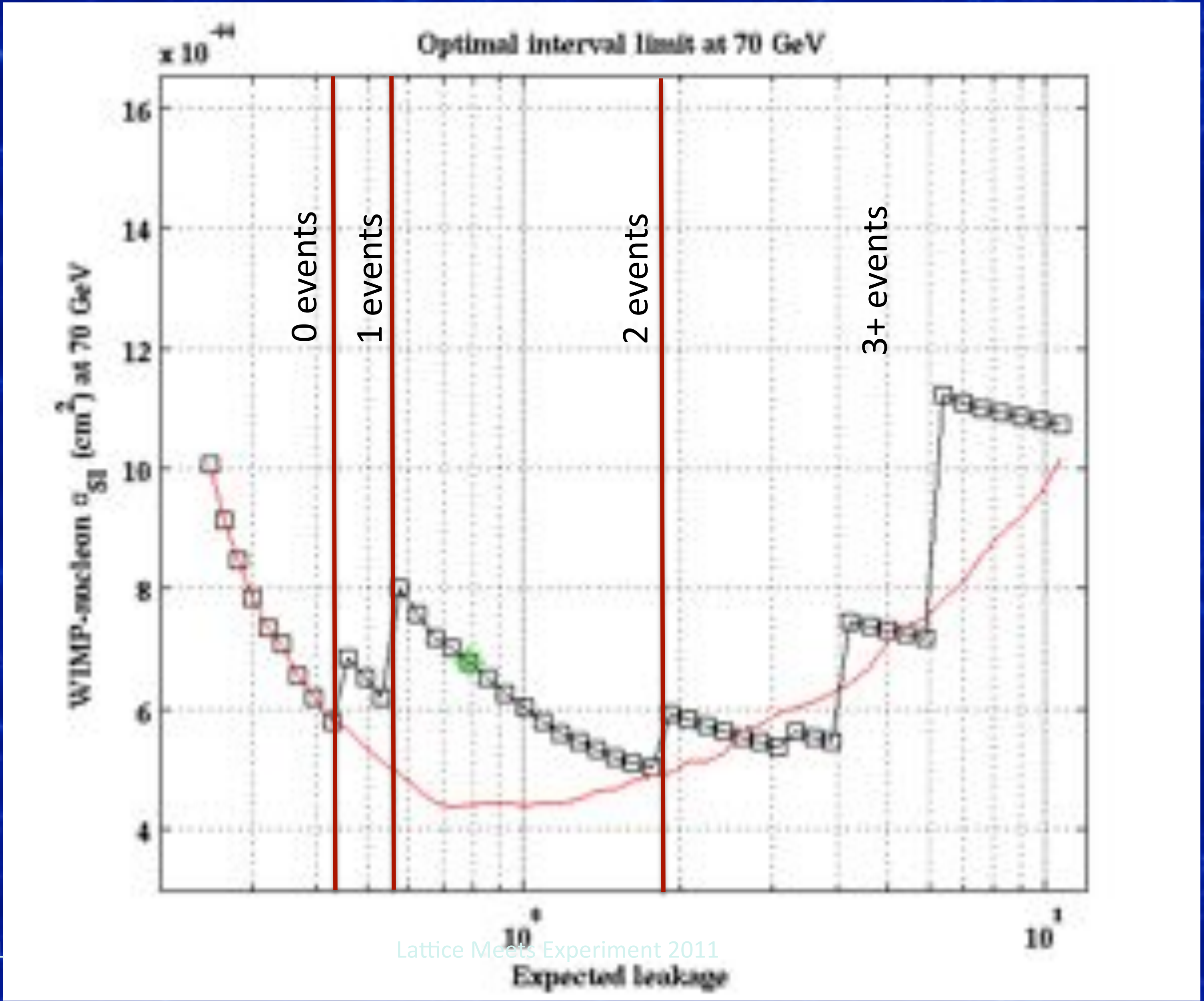
The End

Muon Veto

- Liquid scintillator bundt cake
  - Recycled photodetectors
  - Recycled oil (thanks to NuTeV)
  - Minimum of 10 inches above and surrounding the chamber
- Polyethylene shielding below and in cracks



Cut Position



Likelihood Analysis

- Comparing nuclear scatters from neutron calibrations to surface electron scatters from gamma calibrations
- Likelihoods constructed only for the detectors that recorded the candidate events
- 3 independent methods constructing the likelihood distributions
  - Use of variety of methods helps check technique dependent systematic errors
  - Binned/Unbinned
  - Distribution fitting/no fitting
  - 2D (yield, timing) / 3D (yield, timing, energy)

Likelihood Results (over entire distribution)

- What is the probability of observing one surface electron event with a nuclear scattering likelihood greater than the candidate events in these detectors?

Event	Unbinned 3D	2D with fit	2D no fits
1	24 +/- 5 %	12 +/- 2 %	12 +/- 2 %
2	4 +/- 2 %	5 +/- 1 %	5 +/- 1 %

Likelihood Results
(in the acceptance region)

- What is the probability that a true nuclear recoil in the acceptance region is as close to the cut boundaries as the observed events in these detectors?

Event	Unbinned 3D	2D with fit	Unbinned 2D no fit
1	1 %	3 %	4 %
2	12 %	2 %	19 %

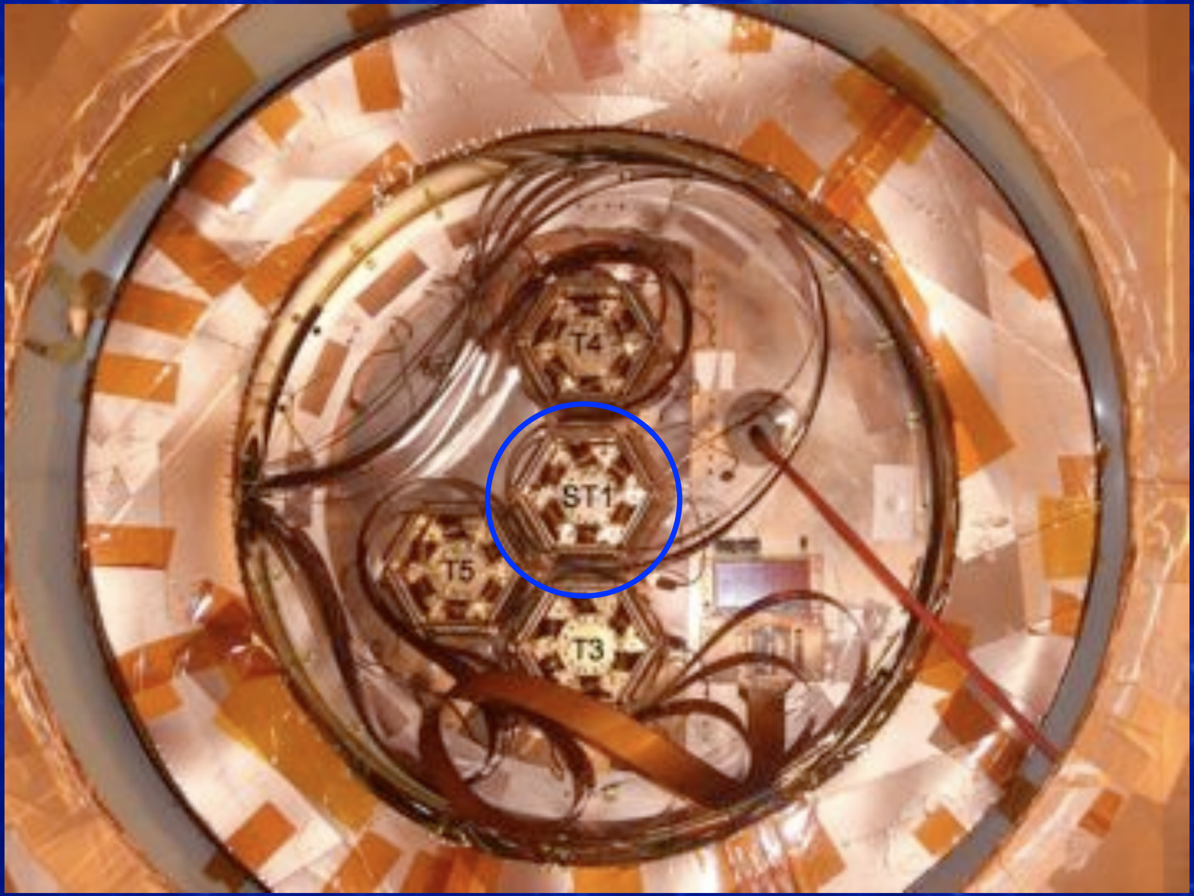
- What is the probability of an electron recoil in the acceptance region appearing to look more like nuclear recoils in the acceptance region in these detectors?

Event	Unbinned 3D	2D with fit
1	83 %	28 %
2	54 %	34 %

Likelihood Summary

- The results verify the initial calculation that the probability of observing two surface backgrounds appearing as nuclear recoil like is low, but not significantly low
- The results encourage suspicion that the observed events are due to surface electron scatters, especially event 1

SuperCDMS Soudan



CDMS II data-taking ended March 2009

First SuperTower data run complete (five 0.65 kg Ge detectors)

Detector background based on α rates below goal in all detectors

Currently analyzing data for surface background characterization

See afternoon talk by P. Brink for detector details and developments!

CDMS Conclusions

- CDMS-II operations complete
  - Limits on direct WIMP-nucleon scattering at the level of 7 x 10^{-44} cm^2 at 70 GeV WIMP mass
- Two events observed
  - Consistent with 0.9 ± 0.2 events expected from known backgrounds
  - Neither are golden events
    - Likelihood encourages suspicion about one event
    - Event reconstruction encourages suspicion about the other event
  - No obvious errors to exclude either event
- The search continues with more massive detectors

The Collaboration

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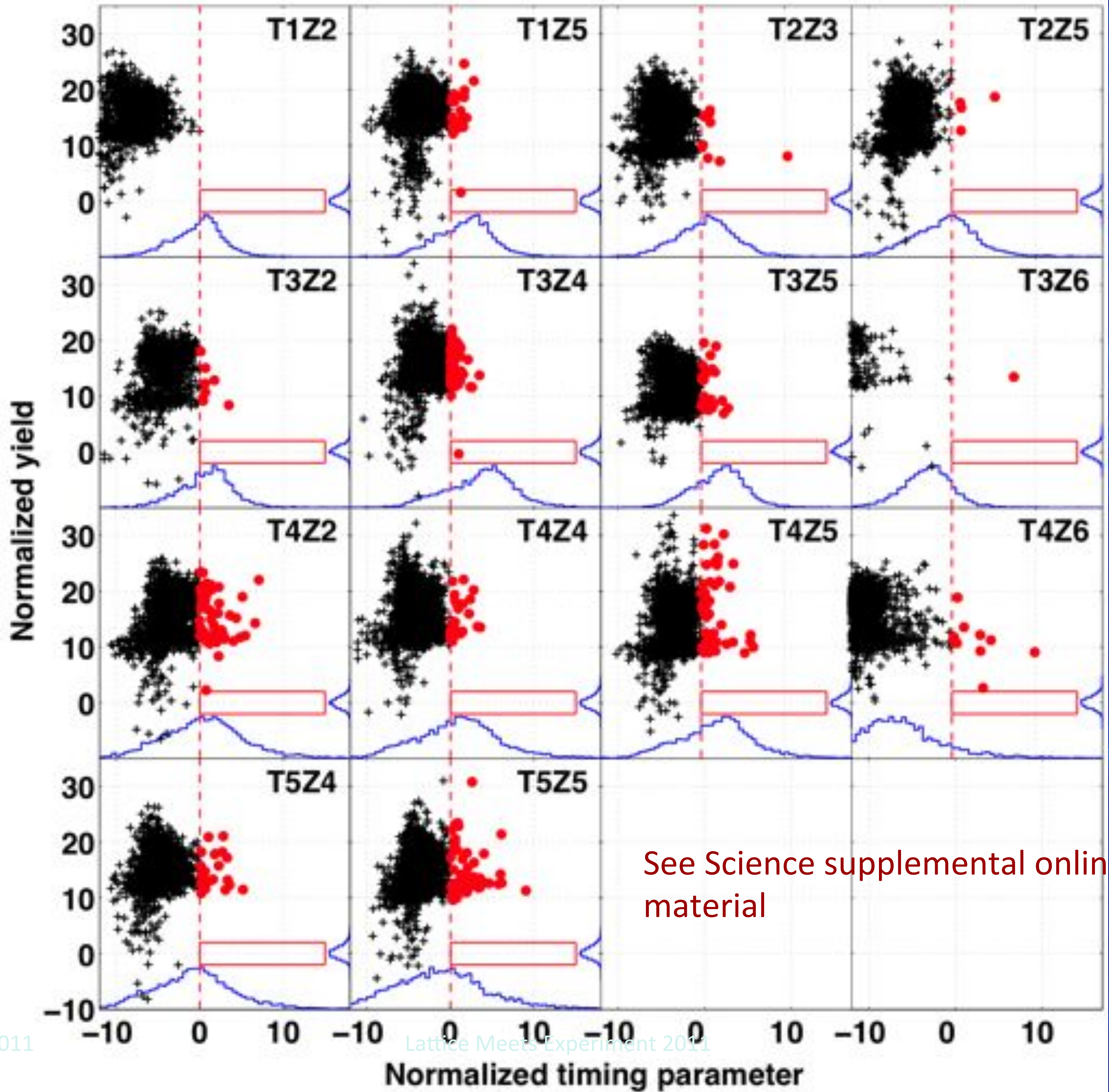
** new collaborators or new institutions in SuperCDMS*



See Science supplemental online material